EFFECT OF QUANTITY AND FREQUENCY OF IRRIGATION ON GROWTH CHARACTERISTICS AND SOIL WATER BALANCE OF TOMATOES IN GREENHOUSE: CASE STUDY OF KITUI COUNTY

BY

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as university supervisors.

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Date

DEDICATION

This work is dedicated to my mum, my dear wife Ruth and my son Victor. May the Almighty Lord bless you for all the encouragement, help and enduring support.

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ABSTRACT

The study was conducted in two greenhouses located at Matinyani Secondary School and Kyondoni Village, Kitui County, Kenya. Variation of tomato crop growth characteristics, yield and soil water content were monitored. These growth characteristics included plant height, stem diameter, fruit diameter and fruit weight.

Four irrigation water application levels served as treatments. These were 120, 100, 80 and 60 % of crop water requirements computed using Priestley-Taylor model (T_1-1.2, T_2-1.0, T_3-0.8 and T_4-0.6). The irrigation frequencies corresponded to daily and alternate (skipping one day) at Matinyani and Kyondoni respectively. Applied irrigation water varied from 548 to 274 mm for daily irrigation and from 255 to 128 mm for alternate irrigation while actual evapotranspiration varied from 537 to 246 mm for daily irrigation and from 227 to 108 mm for alternate irrigation for all treatments.

A significant reduction in growth parameters (plant height, plant diameter and stem diameter), yield and soil water content was observed based on reductions in irrigation water applications and frequency. Daily irrigated treatments produced the best growth parameters, the best fruit quality and the highest yield. In this regard, treatment T_1 produced the largest stem diameter, plant height, fruit weight, fruit diameter and the highest yield as 16.74 mm, 2.31 m, 129 g, 62 mm and 4.44

kg m^{-2} respectively while treatment T_4 produced the highest IWUE and WUE as 11.90 and 13.26 kg m^{-3} respectively.

The average water requirement per plant per day for Anna F_1 tomato variety was 1.35 litres at Matinyani and 1.28 litres at Kyondoni. This variation was attributed to the changes in the microclimate within the greenhouses which could have been due to the changes in the global climate. Open field cultivation is low yielding and risk prone in Kitui County hence the use of greenhouses will protect crops from harsh weather alongside decreasing crop water requirements because the plastic cover creates a barrier to moisture loss.

The results of this study revealed that the growth parameters and yield in treatment T_3 were not different from those in treatments T_1 and T_2. Therefore, in situations where water resources are scarce, treatment T_3 (80 % ETc) on daily irrigation frequency is considered the appropriate quantity for tomato crop grown in a greenhouse and therefore recommended.

An understanding of tomato growth characteristics and soil water balance will provide alternative means by which proper and efficient water management practices in greenhouses can be achieved. Further, a study of this nature can help in understanding the total optimal amount of water required to raise a crop in a greenhouse and this would help in estimating the size of storage facilities needed to store the amount of water harvested from the greenhouse.

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ABBREVIATIONS AND SYMBOLS

A	Gross area per plant
a, b, c, d	Empirical coefficients
asl	above sea level
As	Surface area
BD	Bulk density
C	Vapour removed by condensation
CAN	Calcium ammonium nitrate
CAP	Class A pan
Cp	Specific heat of the air at constant pressure ($Jkg^{-1}K^{-1}$)
CWR	Crop water requirements
D	Drainage (mm)
d	Equivalent depth (m)
DAP	Di-ammonium phosphate
DAT	Days after transplanting
DOY	Day number of the year
E	Crop transpiration
e_a	Actual vapour pressure (kPa)
Ec	Electrical conductivity
e_d	Vapour pressure at mean daily dew point temperature (kPa)
e_s	Saturation vapour pressure (kPa)
ETc	Crop evapotranspration
ETo	Reference crop evapotranspiration
FAO	Food and Agriculture Organization
FC	Field capacity
G	Soil heat flux density (MJ m^{-2} day^{-1})
H	Plant height
IW	Irrigated water

IWP	Irrigation Water Productivity
IWUE	Irrigation water use efficiency
k	Conversion factor
Kc	Crop coefficient
K_t	Unit conversion factor (86400 s day^{-1})
L	Soil depth increment
LAI	Leaf area index
M_s	Mass of dry soil
M_w	Mass of water evaporated
P	Atmospheric pressure (kPa)
P	Fraction representing shading by canopy
PAR	Photosynthetic active radiation
PE	Polyethylene
PWP	Permanent wilting point
θv	Volumetric water content
R	Run-off
R_a	Extra-terrestrial solar radiation (MJ m^{-2} day^{-1})
r_a	Aerodynamic resistance (s m^{-1})
r_c	Canopy resistance (s m^{-1})
RH	Relative humidity (%)
R_{ln}	Net longwave radiation ($MJm^{-2}day^{-1}$)
R_n	Net radiation (MJ m^{-2} day^{-1})
R_{ns}	Net short wave radiation (MJ m^{-2} day^{-1})
r_R	Radiative resistance (s m^{-1})
R_s	Ground level solar radiation (MJ m^{-2} day^{-1})
R_{so}	Daily clear day irradiance ($MJm^{-2}day^{-1}$)
S	Stem diameter
SC	Sandy clay
SCL	Sandy clay loam

T	Mean daily air temperature
T_a	Ambient air temperature
T_m	Daily mean temperature
T_o	Leaf temperature
T_s	Cover surface temperature
U_d	Mean daytime wind speed (m/s)
u_z	wind speed (m/s)
V	Vapour removed by ventilation
VPD	Vapour pressure deficit (kPa)
W_f	Wind function
WUE	Water use efficiency
Z	Elevation above sea level
α	Priestley–Taylor coefficient
α	Albedo (0.23 for green crop)
α_η	Heat coefficient (W m^{-2} K^{-1})
Δ	Slope of saturation vapour pressure curve (kPa °C^{-1})
ΔS	Change in soil water storage (mm)
ε	Ratio molecular weight of water vapour/dry air (0.622)
ε'	Net emissivity
γ	Psychrometric constant (kPa °C^{-1})
λ	Latent heat of vaporization (MJ kg^{-1})
θ_μ	Mass water content (g g^{-1})
η	Irrigation efficiency
ρ	Mean atmospheric density (kg m^{-3})
ρ_b	Density of water (g cm^{-3})
ρ_w	Soil bulk density (g cm^{-3})
σ	Stefan-Boltzman constant (MJ m^{-2} K^{-4} day^{-1})

CHAPTER 1: INTRODUCTION

1.1. Background

Crop cultivation in semi-arid environments is subject to various stresses which include heavy rainfall during the rainy season, water shortages during the dry season, insect infestation and harsh weather characterized by high air temperature and high solar irradiance (Impron, 2011). Consequently, the high evapotranspiration potential experienced in these regions leads to high water use for crop production which according to Sabeh (2007) is about 90% of the fresh water resources used for agriculture. Due to these challenges, open field cultivation in semi-arid regions has remained difficult to practice.

Availability of water is the most important factor limiting development of agriculture in arid and semi-arid regions (Bozkurt and Mansuroglu, 2011). Simba (2010) argues that water is the main input in horticulture which affects both quality and quantity of yield directly. Competition for water has intensified owing to the rapidly accelerated population growth, industrialization and urbanization which have resulted to significant decrease in the actual level of per capita water supply for the last 50 years in many countries (Igbadun *et al*., 2008; Kuo *et al*., 2006). The significant population growth has led to the drastic drop of the per capita share of water to less than 1000 (approximately 700 m^3 $capita^{-1}$) which by international standards is considered the "water poverty limit" though this value may even decrease to 584 m^3 per capita in the year 2025 (Abd El-Rahman, 2009).

Nonetheless, water is still crucial for the economy, health and welfare of the growing world population. In this regard, the declining trend of water in quantity and quality has resulted in an increasing need for the development of methodologies to conserve it on a field, watershed and regional scale. Thus, efficient use of fresh water resources should be an obligation of each user. Although water resources have become increasingly scarce and the need becomes more pressing, newer and more complete methods of measuring and evaluating techniques of handling water resources are necessary.

1.2. Statement of the Problem

Greenhouses have become very popular in Kitui County, Kenya with most companies citing them as goldmines that offer the most profitable business opportunities which no farmer ought to miss. This follows a very aggressive promotion that takes advantage of the fact that farmers are desperate to get more profit from farming but in reality they lack relevant experience in this technology. Moreover, the fact that in the global and competitive marketplace, the high capital investment for greenhouse production systems must be justified by the ability of the farmers using this technology to provide year - round high quality produce to secure long term markets has not been put into consideration.

Water has been scarce in Kitui County but surprisingly farmers with inadequate supply are using more than is needed to raise a crop in a greenhouse. Farmers have devised their own system of management for their greenhouse irrigation systems and this has resulted in varied performance levels. Precisely, greenhouse cultivation as practiced by many farmers in the county is often based on traditional methods of water distribution and application which fail to measure and optimize the supply needed to satisfy the variable water requirements of different crops.

Under the scarce water resources in Kitui County, maximum greenhouse production can be realized through maintaining soil moisture within the crop's rooting zone at close to field capacity throughout the growing season. In this regard therefore, the exact assessment of water requirement of crops will help in devising ways for well designed irrigation scheduling, distribution of water, and reduction in field application losses which ultimately ensures better irrigation efficiencies. It is therefore quite essential and urgent to investigate the crop response to different water application levels alongside assessing the soil water balance to ensure proper management of irrigation and control of application depths in order to apply water effectively according to crop needs.

1.3. Justification

According to Moller and Assouline (2006), modern agriculture in arid and semi-arid regions depends on irrigation. In order to meet the growing needs of the growing population in third world countries, irrigation practices have been adopted as methods of increasing agricultural production per unit volume of water, per unit area of cropped land per unit time (Dunage *et al.*, 2009). Jaria (2012) indicated that 40 % of global crop production comes from the 18 % of irrigated agricultural lands and creates employment to about 30 % of the global population in rural areas. Further, Jaria (2012) reported that irrigation contributes significantly to global food security in Asian countries and it represents almost two-thirds of the total global irrigated area. For example, agriculture which is dependent on irrigation in the Middle East countries such as Iraq, Saudi Arabia and Iran is therefore expected to account for 92 %, 84 % and 73 % respectively of all the agricultural production.

With approximately 70% of fresh water in the world used for irrigation, there is a strong need to find alternatives to traditional farming and irrigation practices (Kulkarni, 2011). In order to increase crop water use efficiency (WUE) in arid and semi arid areas, new innovations for saving irrigation water need to be established. In connection with this, the rise of scientific management revolution of irrigation has been suggested as an option for reducing water use and at the same time increase the water use efficiency of crop production in arid and semi-arid regions (Dunage *et al.,* 2009). This revolution recognizes the fact that water as a resource in agriculture has become a limiting factor in these regions because rainfall distribution is uncertain and erratic in both time and space. This has therefore raised the need to use the available water resources through more efficient methods of water application such as drip irrigation in protected cultivation conditions.

The horticultural sector has undergone a specialized development commonly referred to as protected cultivation. This development entails the cultivation of crops inside a greenhouse covered with plastic films or glass (Simba, 2010). The need to provide fresh quality products during prolonged periods of the year alongside optimizing water use under dry and hot climatic conditions has triggered the adoption of this technology (Casanova *et al.*, 2009). Most importantly, this farming system provides and maintains a controlled environment suitable for optimum crop production (Harmanto *et al*., 2005).

Crop production in a greenhouse reduces irrigation water requirements and produces yields that are about five to ten times greater than in the field (Sabeh, 2007; Vox *et al.*, 2010). Apart from increased crop yield, a better control of crop production in a greenhouse results in improved quality because the inside microclimate and irrigation are much more easily controlled to favour crop growth and development (Harmanto *et al.*, 2005; Orgaz *et al.*, 2005). Impron (2011) argues that with greenhouse farming, production throughout the year which is possible as opposed to open field farming. Further, with protected system of crop production, cleaner crops are produced at better quality with less pesticide, less water, less land and precise fertilizer inputs compared to open field production. Lastly, greenhouses offer an opportunity to farmers in arid and semi-arid regions to harvest water during rain events.

However, in order to achieve profitable and sustainable production in greenhouses, water must be applied in proper amounts and at the appropriate times. In this regard, drip irrigation has been commonly used in greenhouses in exercising control over water application. This is because it enables accurate application of irrigation amounts according to crop water requirements and reduces water losses by soil evaporation and drainage when properly managed. According to Tabatabaei *et al*. (2011), water productivity in greenhouses is a priority and it can be improved by increasing the yield (including product weight, product diameter, stem diameter, and leaf area index) in return for the consumptive water unit. Thus, the degree of production is increased through protecting available water resources and for that matter the increase in yield for consumptive water unit is an activity worthy consideration in the greenhouse.

1.4. Objectives

The broad objective of the study was to assess the effect of water application levels on growth characteristics and soil water balance of tomato crop grown under greenhouse conditions in a semi-arid environment. The specific objectives of the study were to;

1. Assess the variation in microclimate characteristics inside a greenhouse during crop growth period.
2. Establish the crop water requirements based on the microclimate variables monitored in (1) above.

3. Evaluate the effect of selected irrigation water application levels and frequencies on plant growth characteristics, soil water balance and yield during crop growth period.
4. Investigate the soil properties and water use characteristics in the greenhouses under investigation with respect to irrigation water use efficiency (IWUE) and water use efficiency (WUE).

CHAPTER 2: LITERATURE REVIEW

2.1. Evapotranspiration in Greenhouses

Irrigation water maintains the structural form of plants grown in a greenhouse and delivers water and nutrients throughout the plant via transpiration (Sabeh, 2007). Thus, the fate of water in the greenhouse as well as the water requirements of crops depends on evapotranspiration, a process which is driven by a constant inflow of energy (Simba, 2010). Mpusia (2006) stated that evapotranspiration rate inside a greenhouse is an important component of plant canopy energy and water balance and therefore its estimation is important for climate and irrigation control.

El Moujabber and Abi Zeid Daou (1999) reported that modern glass houses reduce light input by at least 30 % which simultaneously causes a considerable reduction in evapotranspiration. These differences affect the evapotranspiration of the crops inside the greenhouse. The percentage of relative humidity inside the greenhouse is higher than that outside and this consequently leads to a reduction in evapotranspiration though its impact is balanced by the high temperatures inside the greenhouse (Casanova *et al*., 2009). Moreover, there is a reduction in exchange of water vapour between the plant canopy and the atmosphere due to lower wind velocity inside the greenhouse (Casanova *et al*., 2009). Junzeng *et al.* (2008) concluded that greenhouses greatly reduce evapotranspiration by decreasing the radiation transmission coefficient and interrupting ventilation hence lowering evaporative demand.

2.1.1. Energy Balance

Evaporation of water requires energy whose availability depends on the microclimate of the greenhouse. Fazlil-Ilahi (2009) argued that crop transpiration is the most important energy dissipation mechanism which influences evapotranspiration rate in greenhouse cultivation. The greenhouse system consists of several components which affect the energy balances inside it (Popovski, 1997). These components include the cover, inner air, plant canopy and soil. Energy transfer in the greenhouse therefore occurs in a combination of four distinct ways; conduction/convection, radiation, latent (water evaporation), and infiltration (Fazlil-Ilahi, 2009; Giacomelli, 2002; Wee, 2010). In a greenhouse therefore, evapotranspiration includes the energy balance of net radiation from the sun, transfer of heat and vapour from a canopy.

The formulation and manufacture of the greenhouse cover determines the transmission of heat by radiation. The plastic cover changes locally the radiation by entrapping long-wave radiation and creates a barrier to moisture losses (Casanova *et al.* 2009). The internal radiation balance is therefore altered with respect to the external environmental conditions especially with regard to absorption and reflection of incident solar radiation.

Since greenhouse environments fall within the broader categorization of "man modified climates", the energy balance approach formalizes the environmental control that greenhouse design and management exerts on the microclimate. The thermal environment of the greenhouse is a function of the radiation energy transmitted into the greenhouse, to that re-emitted through the glazing (Wee, 2010). However, the interaction between greenhouse cover with solar radiation determines how much radiation is transmitted and available at crop level (Fazlil-Ilahi, 2009). This interaction can be determined by the optical laws of reflection, absorption and transmission of the greenhouse cover material.

The solar radiation can be divided into direct radiation which is originating from the sun and diffuse radiation which is scattered in the atmosphere by the clouds (Popovski, 1997). Although the solar energy flux at earth level is within the wavelength region between 300 and 2500 nm, the wavelength of interest for plant growth is PAR and ranges between 400 and 700 nm (Fazlil-lahi, 2009; Giacomelli, 2002; Popovski, 1997). However, only a small part of the PAR energy is absorbed by the crop and is directly converted into the photosynthesis process where as the remainder in converted into heat.

The exchange of greenhouse air with the greenhouse internal surfaces such as cover, plant canopy and soil surface in addition to the exchange between the outer surface of the greenhouse and the ambient air is by convection (Giacomelli, 2002). This process determines a large part of the microclimate inside a greenhouse mainly because quite often the greenhouse cover exchanges energy at the inner surface to the greenhouse air and to the outside air. The systems needed for environmental control in a greenhouse are determined by the energy transfer in and out of the greenhouse which affects the internal greenhouse environment (Sabeh, 2007). Natural convection occurs inside the greenhouse due to low air velocity resulting from the existing temperature differences while forced convection outside the greenhouse is due to air velocities generated by the wind field. The convective heat exchange is represented by equation (2.1):

$$q_{conv} = \alpha_h A_s (T_a - T_s) \quad [2.1]$$

Where,

Ta	Ambient air temperature (K)
Ts	Cover surface temperature (K)
As	Surface area (m^2)
α_h	Heat coefficient ($W\ m^{-2}\ K^{-1}$) which is dependent on fluid properties and system parameters for a particular geometry of the cover.

Infiltration and ventilation involve the transfer of heat by the movement of air through the greenhouse covering (Giacomelli, 2002). In principle, the energy transferred across the control surface involves both sensible and latent heat exchanges (Fazlil-Ilahi, 2009). In general, the energy balance of a crop is from the absorption of solar radiation particularly the photosynthetic active radiation (PAR), the exchanged sensible and latent heat and the thermal radiative exchange with the various greenhouse parts.

2.1.2. Water Vapour Balance

The concentration of water vapour in the air affects plant transpiration by creating a vapor pressure differential between the plant leaf and the air (Sabeh, 2007). The vapour pressure deficit (VPD) drives moisture from the plant into the air. However, the transfer of water vapour into and out of the greenhouse determines the moist air conditions. By convention, using the greenhouse air as the control volume, the control surfaces comprise the glazing, ground, plants and any open points of entry such as vents and gaps in the structure (Sabeh, 2007). Through condensation and ventilation processes, vapour is removed from the greenhouse according to the equation (2.2) proposed by (Fazlil-Ilahi, 2009):

$$E - C - V = 0 \qquad [2.2]$$

Where,

E	Crop transpiration
C	Vapour removed by condensation
V	Vapour removed by ventilation

The amount of water vapour contained in a given volume of air is determined by the temperature of air within the greenhouse. In addition, the amount of water vapour that a given volume of air can absorb at a particular temperature is determined by relative humidity and vapour pressure within the greenhouse.

2.2. Water Requirements inside a Greenhouse Environment

Water requirement inside a greenhouse can be either higher or lower than in the open field (Sharan and Jadhav, n.d). They reported that water requirement is higher if the greenhouses are heated like those in temperate climates and lower in unheated greenhouses like those used in hot and tropical regions. Mpusia (2006) reported that the use of greenhouse in arid and semi-arid regions decreases crop water requirements because the plastic cover creates a barrier to moisture loss.

Greenhouse agriculture provides a way of increasing crop water use efficiency (Mpusia, 2006; Sharan and Jadhav, n.d). They argued that protected cultivation has the potential benefit of substantially increasing plant productivity per unit water consumption which is important in many areas where good quality water sources are severely limited.

According to El Moujabber and Abi Zeid Daou (1999), greenhouses reduce crop evapotranspration to about 70% of open field rates hence improving water use relative to unprotected cropping by approximately 50%. Harmanto *et al*. (2005) demonstrated that crop water requirements computed from climatic data measured inside the greenhouse was about 75 – 80 % the crop water requirements computed with the climatic parameters observed in the open environment. Mpusia (2006) reported that greenhouse farming system performed better than open farming systems in terms of irrigation water productivity, crop yield as well as fruit quality. Orgaz *et al.* (2005) reported that the seasonal evapotranspiration of horticultural crops grown in greenhouses was relatively low due to the lower evaporative demand inside the greenhouse compared to irrigated crops outdoors and that off-season greenhouse crops were grown during low evaporative demand periods hence low water requirements. In conclusion, for regions subject to acute water shortages, greenhouse cultivation can actually reduce the water usage per unit yield by about 50% (Mpusia, 2006).

2.3. Evapotranspiration Models in Greenhouse

Fazlil-Ilahi (2009) and Abedi-Koupai *et al*. (2009) stated that water management for greenhouse cultivation is depended on accurate estimation of evapotranspiration rate inside the greenhouse. Evapotranspiration of a well irrigated crop is calculated using the crop coefficient (Kc) and ETo (Allen *et al*., 1998) as follows:

$$ETc = Kc * ETo \qquad [2.3]$$

El Moujabber and Abi Zeid Daou (1999) reported that Class A Pan evaporation method, the FAO radiation and Priestley-Taylor models are presumed to give reliable measurements of protected crop water requirements in greenhouses. Liu *et al*. (2008) computed reference crop evapotranspiration inside the greenhouse with the following commonly used models; Priestley-Taylor, FAO-Radiation, Hangreaves, FAO-Penman, and FAO 56 Penman-Monteith.

2.3.1. FAO Penman Model

Abedi-Koupai *et al*. (2009) observed that Penman accounted for the energy required for evaporation, and also recognized the need to account for the aerodynamic energy (wind) required for the removal of water vapor from leaf surfaces. The FAO-Penman model is an improved model in which the wind function is more sensitive than was used originally by Penman in 1948 (Abedi-Koupai *et al*., 2009). The FAO Penman model is of the form:

$$\mathrm{ETo} = \frac{1}{\lambda}\left\{\left[\frac{\Delta}{\Delta + \gamma}\right](R_n - G) + \left[\frac{\gamma}{\Delta + \gamma}\right](6.43)(W_f)(VPD)\right. \qquad [2.4]$$

$$W_f = 1 + 0.0536u_z \qquad [2.5]$$

Where,

λ	Latent heat of vaporization (MJ kg^{-1})
R_n	Net radiation at the crop surface (MJ m^{-2} day^{-1})
G	Soil heat flux density (MJ m^{-2} day^{-1})
Δ	Slope of saturation vapour pressure curve (kPa $°C^{-1}$)
γ	Psychrometric constant (kPa $°C^{-1}$)
W_f	Wind function
VPD	Vapour pressure deficit (kPa)
u_z	Wind speed at z (m) height

The Penman method is not commonly used in greenhouses because of the difficulty of obtaining accurate wind measurements (Abedi-Koupai *et al*., 2009).

2.3.2. FAO Penman-Monteith Model

According to Allen *et al*. (1998), FAO Penman-Monteith model simulates a reference crop of 0.12 m in height with a surface resistance of 70 sm^{-1} and an albedo of 0.23. The model estimates evaporation from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and under non-limited soil water. The model uses standard climatological records of solar radiation (sunshine), air temperature, humidity and wind speed (Allen *et al*., 1998). The FAO Penman- Monteith model for the calculation of daily ET_o (mm day^{-1}) is of the form:

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad [2.6]$$

Where,

ET_o	Reference evapotranspiration (mm day^{-1}),
Rn	Net radiation at the crop surface (MJ m^{-2} day^{-1}),
G	Soil heat flux density (MJ m^{-2} day^{-1}),
T	Mean daily air temperature at 2 m height (°C),
u_2	Wind speed at 2 m height (ms^{-1})
e_s	Saturation vapour pressure (kPa),
e_a	Actual vapour pressure (kPa),
$e_s - e_a$	Vapour pressure deficit (kPa),
Δ	Slope of saturation vapour pressure curve (kPa $°C^{-1}$),
γ	Psychrometric constant (kPa $°C^{-1}$).

The main limitation of the FAO Penman-Monteith model to compute tomato evapotranspiration is that it requires wind speed which is difficult to measure in greenhouse conditions.

2.3.3. FAO - Radiation Model

The FAO radiation model is based on solar radiation and it gives adequate ETo results in high humidity conditions where the aerodynamic element is relatively small, as in greenhouse conditions, whereas results become erratic in dry conditions (Casanova *et al.*, 2009). The model is described as follows:

$$\mathrm{ETo} = \mathrm{b}\left[\frac{\mathrm{R_s}}{\lambda}\,\frac{\Delta}{\Delta + \gamma}\right] - 0.3 \qquad [2.7]$$

$$\mathrm{b} = 1.066 - 0.13\mathrm{x}10^{-2}\mathrm{RH} + 0.045\mathrm{U_d} - 0.20\mathrm{x}10^{-3}\mathrm{RHxU_d} - 0.315\mathrm{x}10^{-4}\mathrm{RH}^2 - 0.11\mathrm{X}10^{-2}\mathrm{U_d^2} \qquad [2.8]$$

Where,

Rs	Solar radiation (cal cm^{-2} day^{-1})
λ	Latent heat of vaporization (MJ kg^{-1})
Δ	Slope of saturation vapour pressure curve (kPa $°C^{-1}$)
γ	Psychrometric constant (kPa $°C^{-1}$)
b	Dimensionless parameter
RH	Relative humidity
U_d	Mean daytime wind speed (ms^{-1})

The FAO radiation model is not commonly used in greenhouses because of the difficulty of obtaining the aerodynamic term (Abedi-Koupai *et al.*, 2009).

2.3.4. Priestley-Taylor Model

The Priestley-Taylor model can be used estimate the potential evapotranspiration of different types of vegetation (Fazlil-Ilahi, 2009; Hector *et al.*, 2009). Donatelli *et al.* (2006) stated that the Priestley-Taylor model is useful for the calculation of daily ETo for conditions where weather inputs for the aerodynamic term (relative humidity and wind speed) are unavailable. The aerodynamic term of Penman-Monteith model is replaced by a dimensionless empirical multiplier (α: Priestley-Taylor coefficient). The weighting factor corrects the effect of solar radiation, the wind and humidity on ETo (Theocharis, 2009). The model is of the form:

$$\mathrm{ETo} = \frac{1}{\lambda} \propto \frac{\Delta}{\Delta + \gamma}(\mathrm{Rn} - \mathrm{G}) \qquad [2.9]$$

Where,

α	Empirical coefficient
Δ	Slope of the saturation vapor pressure curve ($kPa°C^{-1}$).
λ	Latent heat of vaporization ($MJkg^{-1}$)
γ	Psychometric constant ($kPa\ °C^{-1}$)
R_n	Net radiation ($mm\ d^{-1}$)
G	Soil heat flux ($mm\ d^{-1}$)

The value of α depends on vegetation type and could be related to sensible heat flux of the surface and vapor pressure deficit and has a value α = 1.12 (Hector *et al.*, 2009). The value of G is negligible in the daily calculation of potential evapotranspiration because it is small on daily basis (Allen *et al.* 1998; Hector *et* *al.* 2009). Similarly, Donatelli *et al*. (2006) suggested a G value of zero in computing crop evapotranspiration for tomato crop grown in a greenhouse using the Penman-Monteith and Priestley-Taylor models.

2.3.5. Hargreaves Model

The Hargreaves ETo model was developed in 1985 and requires only measured temperature data (Hargreaves and Samani, 1985; Liu *et al*., 2008). This model can be used as an alternative when solar radiation data, relative humidity data or wind speed data are unavailable (Allen *et al*., 1998). The Hargreaves temperature based model is of the form:

$$\mathrm{ETo} = \frac{1}{\lambda}\,(0.0023)(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a \qquad [2.10]$$

Where,

λ	Latent heat of vaporization (MJ kg^{-1})
Ra	Extra-terrestrial solar radiation (MJ m^{-2} day^{-1})
T_{max}	Maximum daily air temperature (°C)
T_{min}	Minimum daily air temperature (°C)
T_{mean}	Mean daily air temperature (°C)

The limitation with this model is that it requires measurement of extra-terrestrial solar radiation which is difficult to measure in greenhouse conditions.

2.3.6. Stanghellini Model

Stanghellini (1987) revised the Penman-Monteith model to represent conditions in a greenhouse where air velocities are less than 1 m s^{-1}. This model includes calculations of the solar radiation heat flux derived from the empirical characteristics of short wave and long wave radiation absorption in a multi-layer canopy. The model uses leaf area index (LAI, m^2 m^{-2}) to account for energy exchange from multiple layers of leaves on greenhouse plants.

The model is of the form:

$$ET = 2\ LAI\ \frac{1}{\lambda}\ \{\frac{s(R_n - G) + K_t\left[\frac{VPD\ \rho\ C_p}{r_R}\right]}{s + \gamma\left[1 + \frac{r_c}{r_a}\right]} \qquad [2.11]$$

$$R_n = \frac{0.07R_{ns} - 252\rho C_p(T - T_o)}{r_R} \qquad [2.12]$$

$$R_{ns} = 0.77\ R_s \qquad [2.13]$$

$$r_R = \frac{\rho C_p}{4\sigma(T+273.15)^3} \qquad [2.14]$$

Where,

ET_o	Reference evapotranspiration (mm day^{-1})
R_n	Net radiation at the crop surface (MJ m^{-2} day^{-1})
G	Soil heat flux density (MJ m^{-2} day^{-1})
K_t	Unit conversion factor equal to 86400 s day^{-1}
VPD	Daily or hourly vapour pressure deficit (kPa)
ρ	Mean atmospheric density (kg m^{-3})
C_p	Specific heat of the air (MJ kg^{-1} $°C^{-1}$)

r_R	Radiative resistance (s m^{-1})
r_c	Canopy resistance (s m^{-1})
r_a	Aerodynamic resistance (s m^{-1})
λ	Latent heat of vaporization (MJ kg^{-1})
s	Slope of saturation vapour pressure curve (kPa °C^{-1})
γ	Psychrometric constant (kPa °C^{-1})
R_{ns}	Net short wave radiation (MJ m^2 day^{-1})
R_s	Ground level solar radiation (MJ m^2d ay^{-1}
T	Hourly or daily mean air temperature (°C)
T_o	Leaf temperature (°C)
σ	Stefan-Boltzman constant (MJ m^{-2} K^{-4} day^{-1})
LAI	Leaf area index (m^2 m^{-2})

The main limitations of Stanghellini model to compute tomato evapotranspiration is that it requires the parameterization of surface canopy resistance (r_c) and aerodynamic resistance (r_a) which are difficult to measure or estimate in greenhouse conditions (Hector *et al*., 2009).

2.3.7. Class A Pan (CAP) method

Fernandez *et al*. (2003) reported that CAP method has been one of the most utilized methods worldwide due to its simplicity, relatively low cost, and yielding of daily evapotranspiration estimates. This is because evaporation pans can be used to measure the combined effect of humidity, sunshine, temperature, and wind speed on water consumption by crops (Baille, 1996). The placement of CAP inside the greenhouse without considering standard reference conditions can be a first step for rough estimation of water demand when there are no other available methods or weather data are lacking (Baille, 1996). However, its use inside greenhouses is still a subject of controversy. Research results about what pan coefficient (K_p) should be utilized inside the greenhouse are not conclusive (Fernandez *et al*. 2003). El Moujabber and Abi Zeid Daou (1999) argued that CAP can be problematic inside the greenhouse because it hampers movement and limits space and for that matter some producers consider leaving an unproductive area of approximately 10 m^2 occupied by the CAP inside the greenhouse not viable.

2.4. Tomato Growth Characteristics and Requirements

Globally, tomato (Solanum Lycopersicum) is the second most important vegetable crop produced after Irish potato (Jaria, 2012). It is a warm season vegetable crop which grows best under conditions of high light and warm temperatures (summer conditions). It is a day length neutral plant under conditions of short or long days and is characterized by rapid growth whose period is between 90 and 150 days (Grey, 2010).

Hendricks (2012) argued that light, carbon dioxide (CO_2), water, adequate temperature and sufficient and proper nutrients are the key requirements necessary for optimal tomato growth. Papadopoulos (1991) reported that air temperature is the main environmental component which influences vegetative growth, cluster development, fruit setting, fruit development, fruit ripening and fruit quality. However, temperatures are adjusted depending on the stage of production (i.e. germination, transplanting, harvesting, etc). In this regard, the optimum mean daily temperature for growth is from 18 to 26 ºC with night temperatures between 18 and 21 ºC (Hendricks, 2012). On the other hand, the general growth of tomatoes is favoured by high relative humidity which when is high during the day can improve fruit setting (Papadopoulos, 1991). However, if high relative humidity is not managed properly, can lead to water condensation on the plants and can cause development of serious diseases.

Generally, tomato can be grown on a wide range of soils but it thrives under well drained, light, loam soil with pH ranging from 5 to 7 (Jaria, 2012). However, it is moderately sensitive to soil salinity. In greenhouses, tomato is grown on local soil or on substrate (soilless culture) and it requires a professional drip system and fertigation system. A heating system is necessary in cold countries, and a cooling system or ventilated greenhouse is required in hot places such as tropical and sub-tropical climates (Hendricks, 2012).

Jaria (2012) reported that tomato crop has four growing stages for the first harvest and he described them as follows: The first is the germination, emergence and establishment stages which take 25 to 35 days. The second is the vegetative stage period which begins from the end of stage one up to flowering and covers 20 to 25 days. The third is flowering which begins from reproductive stage until and extends until the first full size mature green fruit is realized and it usually takes 20 to 30 days from yield formation until 20% of the fruit changes color. The fourth is ripening which takes 15 to 20 days. To this end, a controlled supply of water throughout the growing period is necessary in order to obtain high yield and of good quality (Papadopoulos, 1991). However, under water limiting conditions, some water savings may be made during the vegetative and ripening periods.

2.4.1. Tomato Crop Water Requirements in a Greenhouse

Owusu-Sekyere *et al*. (2009) reported that water is a key factor that determines tomato yield. According to Harmanto *et al*. (2005), greenhouses have been widely used and well developed in temperate areas and as such several studies have been conducted to provide information about the application of micro irrigation in them.

Papadopoulos (1991) reported that water consumption per unit area of greenhouse per year in Netherlands was between 0.5 and 0.9 m^3. Similarly, at different levels of water salinities in Netherlands, Harmanto *et al*. (2005) reported that plant water consumption of tomato crop was between 0.19 to 1.03 litres $plant^{-1}$ day^{-1}. Irrigation water requirements in a greenhouse vary depending on the season and the size of tomato plants cultivated and as such newly transplanted tomato plants require about 0.05 litres $plant^{-1}$ day^{-1} while at maturity especially on sunny days plants requirements may rise to 2.7 litres $plant^{-1}day^{-1}$ (Harmanto *et al.*, 2005). The adequate irrigation amount for a fully grown or nearly fully grown tomato plant inside a greenhouse is about 1.8 litres $plant^{-1}$ day^{-1} (Harmanto *et al*., 2005).

Harmanto *et al*. (2005) recommended that the actual irrigation water for drip irrigated tomatoes grown in a greenhouse located in a tropical environment was between 4.1 and 5.6 mm day^{-1} or equivalent to 0.3 - 0.4 litres plant^{-1} day^{-1}. Hector *et al*. (2009) reported that the seasonal water requirement for tomato crop grown in a greenhouse in Chile was 328.3mm. Chartzoulakis and Drosos (1997) reported that the maximum yields for tomato crop grown in a greenhouse in Crete, Greece, were obtained with seasonal water application of 260 mm. The recommended daily amount of water required by tomato crops cultivated in Indian greenhouses for different growing system varies from 0.89 to 2.31 litres plant^{-1} day^{-1} (Harmanto *et al*., 2005). Junzeng *et al*. (2008) found out that the seasonal total evapotranspiration for tomato crop calculated based on the water balance approach in China was 123.6 mm.

2.4.2. Impact of irrigation on Different Growth Stages of Tomato Crop

Due to the influence of water on crop establishment, fungal problems, fruit set and quality, the management of water is important at all stages of tomato crop development Sezen *et al*. (2006). Tomato transplants should be stressed prior to field setting so that they can more successfully deal with the transition to less favourable field conditions (Jaria, 2012).

During the flowering stage, the water demand for tomato crop is usually the highest and therefore Jaria (2012) recommended that irrigation should be withheld in order to facilitate less mature plants into flowering and to encourage uniform flowering and ripening. Further, in order to avoid flower drop during this stage, any extended water deficiency should be avoided. However, excessive irrigation during the flowering period causes flower drop, reduced fruit set and potential for excessive vegetative growth which leads to delayed ripening (Papadopoulos, 1991). As a consequence, water supply during and after fruit set must be limited to required levels in order to prevent stimulation of new growth at the expense of fruit development. In principle, irrigation management during fruit development and ripening is important since it can greatly influence yield, solids, product quality, and viscosity. Jaria (2012) noted that fruit stress increases soluble solids but reduces yield and viscosity.

2.5. Soil Water Monitoring

Within the context of irrigation water management, Muñoz-Carpena (2004) reported that measuring and monitoring soil water content is an important practice which aims at conserving water and improving its quality. Bittelli (2011) argued that soil water content (SWC) plays a key role in many biophysical processes, such as seed germination, plant growth and plant nutrition alongside affecting processes such as water infiltration, redistribution, percolation, evaporation and plant transpiration.

In the context of horticultural systems, it is important to quantify SWC because it is useful in optimizing irrigation volumes, fertilizer applications and soil-water-budget computations. There are two main ways of measuring soil water for plant growth: first is by measuring soil moisture content and second is by measuring the water potential (Jaria, 2012). The measurement of soil water content is vital for three main reasons: ensuring that soil water content is being kept within the allowable limits, identifying the next water application event, and telling how much water the soil can hold without deep percolation.

Jaria (2012) described soil moisture as gravimetric (mass of soil water divided by weight of dry soil); volumetric water content (volume of soil water in a given volume of soil) and depth of soil moisture per depth of soil (mm of water per metre of soil). The measurement of the moisture content can be accomplished directly or indirectly while the water potential is measured through tensiometry (Grey, 2010).

2.5.1. Direct Methods

Direct methods determine soil water content by accounting for the water removed from a soil sample by evaporation, leaching or chemical reaction processes. Bittelli (2011) pointed out that direct methods are labour intensive, destructive, inapplicable to automatic control and have a long response time of more than 24 hours hence cannot provide time feedback.

However, Muñoz-Carpena (2004) reported that though gravimetric method is a direct method, it is the standard for measuring soil water content because it is often used to verify or calibrate other methods and therefore several researchers have relied on it. Gravimetric measurements involve weighing a sample of moist soil, drying it at a temperature of 105 °C and weighing it again to determine the water loss in which the water weight lost represents the moisture level of the moist sample (Simba, 2010).

2.5.2. Indirect Methods

Indirect methods estimate soil moisture by use of calibrated relationships with some other measurable variables and the suitability of each method depends on the cost, accuracy, response time, installation, management and durability (Muñoz-Carpena, 2004). Indirect methods estimate soil water content based on measurement of soil properties assumed to be correlated with water content (Bittelli, 2011). However, depending on the quantity measured, indirect techniques are either volumetric or tensiometric (Duke *et al*., 2010).

2.6. Soil Water Balance

Jaria (2012) reported that water budgeting is a widely promoted method of irrigation scheduling because it seeks to predict water status by means of a water conservation equation. In principle, a simple single layer water balance model determines daily soil moisture status by accounting for all system inputs and outputs and maintaining favorable soil moisture (Simba, 2010). Mpusia (2006) argued that soil water balance can be established at different time frames for instance hourly, daily etc. and that evapotranspiration can be related to the irrigation water, the change in water stored in the soil or substrate and the amount of water drained out of the greenhouse. The growing medium determines the water storage capacity in the soil and compared to daily uptake, it is high in real soil but considerably less for artificial substrates or systems using nutrient film techniques

The most important components of the water budgeting model in a greenhouse are the accurate determination of irrigation amount, change in soil water storage (content), deep percolation and runoff (Andreu *et al*., 1997; Bozkurt and Mansuroğlu, 2011; Demirtas and Ayas 2009; Hector *et al*., 2009). The general equation of water balance in greenhouses is represented by the following equation:

$$\mathrm{ET} = \mathrm{I} + \Delta S - \mathrm{D} - \mathrm{R} \qquad [2.15]$$

Where,

R	Run-off
ΔS	Change in soil water storage
D	Water net flux at deeper layer
I	Irrigated water quantity
ET	Evapotranspiration

Initial soil moisture status can be determined by the soil moisture instruments or by gravimetric sampling. Jaria (2012) stated that for high soil infiltration capacity relative to irrigation application rate, no surface runoff will occur. Meanwhile, the use of drip irrigation in greenhouses tends to be very efficient specifically applying water at rates less than the soil infiltration capacity and hence deep percolation tends to be minimal (Hector *et al*., 2009). However, if the depth of irrigation is greater than the depth of water depleted from the root zone, the difference is considered as deep percolation or water that is drained below the root zone, and is not available for plants. Thus, with negligible surface run-off and surface deep percolation, equation (2.15) can be further simplified as equation (2.16) (Hector *et al*., 2009):

$$ET = I + \Delta S \qquad [2.16]$$

2.7. Summary of Literature Review

From the review presented above four inferences may be drawn. First, the use of greenhouses in arid and semi-arid regions decreases crop water requirements because the plastic cover creates a barrier to moisture loss (Mpusia, 2006). Hence greenhouses may offer a better solution to the deteriorating agricultural production due to the acute water shortages experienced in these regions.

Secondly, the estimation of evapotranspiration in the greenhouse is very important because it helps in estimation of the microclimate and in controlling irrigation (Mpusia, 2006). In this regard, a substantial number of different experimental models have been developed to estimate evapotranspiration and a large body of knowledge is available on theory and applications. However, the use of any of the models requires measurement of various microclimate variables in the greenhouse. The Priestley-Taylor method was selected for this study because it does not incorporate the wind function which is difficult to measure within the greenhouse (Donatelli, 2006) and it is presumed to give reliable measurements of protected crop water requirements (El Moujabber and Abi Zeid Daou, 1999).

Thirdly, crop water requirement vary from region to region in which case it is higher in greenhouses located in temperate regions and lower in those located in the tropics (Sharan and Jadhav, n.d). Further, irrigation water requirements in a greenhouse vary depending on the season and the size of the plant (Harmanto *et al*., 2005). In particular, the adequate irrigation amount for a fully grown or nearly fully grown tomato plant inside a greenhouse is about 1.8 litres $plant^{-1}$ day^{-1} (Harmanto *et al*., 2005).

Fourthly, measuring and monitoring soil water status is an essential component of the best management practices aimed at conserving water and improving its quality within the context of irrigation water management (Bittelli, 2011). The measurement of the soil water content can be accomplished directly or indirectly (Grey, 2010).

CHAPTER 3: MATERIALS AND METHODS

3.1. Experimental Site

The experiment was carried out in two greenhouses located at Matinyani Secondary School and Kyondoni Location, Kitui County from May to October 2013. The location for Matinyani corresponds to latitude 1^{o} 19′ 16″ S, longitude 37^{o} 58′ 09″ E and altitude1186 m asl while Kyondoni corresponds to latitude 1^{o} 18′ 45.20″ S, longitude 37^{o} 58′ 04.54″ E and altitude 1187 m asl.

Geographically, Kitui County is located in Eastern Kenya (Appendix B). The climate of the county is arid and semi-arid with very erratic and unreliable rainfall. Rainfall ranges from 500 to 1050 mm per annum while temperatures range from 14 ^{o}C to 34 ^{o}C. The long rains occur in April/May and the short rains in November/December. The periods falling between June to September and January to March are usually dry. The soils within the county are reddish sandy clay loam with good infiltration and loose structure.

3.2. Experimental Set up

The greenhouses had the following geometric characteristics: eaves height 2 m, ridge height 4 m, width 8 m and length 15 m. The greenhouse roof was covered with a 200 micron transparent plastic paper treated for ultraviolet radiation. The greenhouse side walls were covered with insect net and had plastic curtains which were raised or dropped depending on the weather fluctuations (fig. 3.1).

Figure 3.1: Sectional view of the greenhouse

Drip irrigation system was used in the experiment and laterals were laid for each plant row. The emitter spacing was at 20 cm intervals and the discharge rates were 1.188 and 0.55 litres hour^{-1} at Matinyani and Kyondoni respectively. The main and sub-main pipelines for drip irrigation were made of polyethylene pipes of 25 mm diameter while linear low density polyethylene pipes of 12 mm and 8 mm diameter were used for the laterals at Matinyani and Kyondoni respectively. The system was operated by water head created by a 500 litre tank raised at a height of 2.4 m above the ground. The control unit of the system consisted of a 500 litres tank, screen filter, main, sub-mains, laterals, drippers, flow meters, control valves and other accessories required for drip irrigation.

In the experiment tomato hybrid Anna F_1 was used as the test crop. Four irrigation water application levels served as treatments. These were: full irrigation (T_2) corresponding to 100 % of ETc, 120 % of ETc (T_1; 20 % excessive), 80 % of ETc (T_3; 20 % deficit) and 60 % of ETc (T_4; 40 % deficit), (figure 3.4). Irrigation amounts were determined using pre-determined coefficients of ETc at the treatment of irrigation levels (Bozkurt and Mansuroglu, 2011; Dunage *et al.*, 2009; Harmanto *et al.*, 2005; Sezen *et al.*, 2006; Owusu-Sekyere *et al.*, 2009). The treatments were designed to evaluate the tomato crop's response to irrigation applications (fig. 3.2).

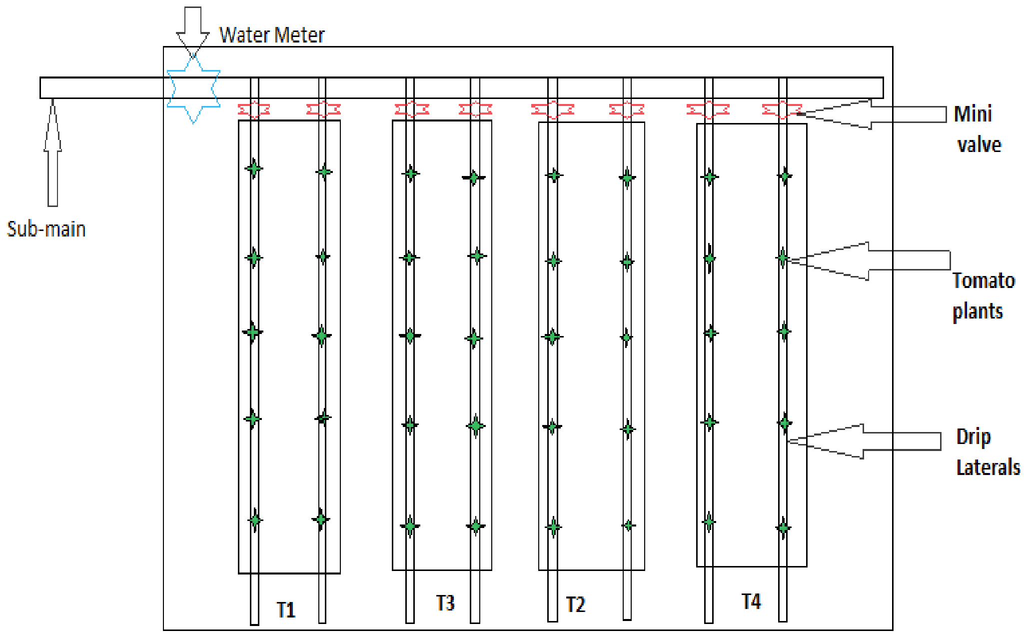

Figure 3.2: Experimental Layout within the Greenhouse

3.3. Experimental Procedure

Tomato seeds were sown on 21st May and 9th July, 2013 and transplanted on 30th June and 6th August, 2013 at Matinyani and Kyondoni respectively. Tomato seedlings were transplanted onto raised beds of width 0.9 m and length 15 m. Each bed had double rows with plant spacing of 60 cm along rows and 40 cm between rows. Irrigation was applied uniformly to all treatments at the beginning of transplanting until 9th July and 16th August, 2013 at Matinyani and Kyondoni respectively for plants to be well established. Thereafter, a fixed irrigation frequency was applied in all treatments. Crops were irrigated daily at Matinyani and by skipping one day (alternate days) at Kyondoni. This selection was meant to evaluate the effect of irrigation frequency on growth parameters, yield and soil water balance of tomato. At Matinyani, the first monitored irrigation was applied on 10th July, 2013 while the last was on 15th September, 2013. Likewise, at Kyondoni, the first monitored irrigation was applied on 17th August, 2013 while the last was on 26th October, 2013.

A common recommended fertilization program was followed in the experiment with all the treatment plots receiving the same amounts of fertilizer which consisted 150 kg ha^{-1} DAP and 200 kg ha^{-1} CAN. All fertilizers were applied manually. Weeding was carried out manually while pests and diseases were controlled using pesticides prescribed from area agro-vet shops. Occurrence of the different growth stages and harvesting time were recorded as days after transplanting (DAT) accordingly.

3.4. Determination of Reference Crop Evapotranspiration based on Greenhouse Microclimate

Potential evapotranspiration (ETo) was computed using Priestley-Taylor model (refer to equation 2.9 in Chapter Two). Data for this model was obtained from meteorological measurements in the greenhouse comprising air temperature, wet bulb and dry bulb temperatures, estimates of net radiation, slope of the saturation vapor pressure curve and psychrometric constant.

3.4.1. Measurements of Microclimate Parameters within the Greenhouse

The main parameters measured within the greenhouse were air temperature, wet bulb and dry bulb temperatures. These parameters were measured from the start of monitoring period up to harvesting in order to establish the variation during the period of the experiment. The minimum and maximum air temperatures in the greenhouse were measured using minimum and maximum thermometers while wet and dry bulb temperatures were measured using dry bulb and wet bulb thermometers (figure 3.3). Soil temperature was measured at 10 cm depth using a soil thermometer (figure 3.4). The minimum and maximum air temperatures were recorded at 9.00 am and 3.00 pm respectively while wet bulb, dry bulb and soil temperatures were recorded at 9.00 am, 12.00 noon and 3.00 pm.

Figure 3.3: Measuring dry bulb and wet bulb temperatures within the greenhouse

Figure 3.4: Measuring soil temperature at 10 cm depth inside the greenhouse

3.4.2. Estimation of Microclimate Parameters within the Greenhouse

The following microclimate parameters were estimated within the greenhouse based on empirical relationships proposed by Allen *et al*. (1998) and Meyer (1999). These microclimate parameters were estimated daily at Matinyani and at alternate days at Kyondoni. This criterion was used in order to investigate the variation of the parameters throughout the experiment period.

3.4.2.1. Estimation of Atmospheric Pressure (P)

Atmospheric pressure (P) is important for estimating the psychrometric constant. P was estimated as follows:

$$P = 101.3\left(\frac{293 - 0.0065\,Z}{293}\right)^{5.26} \qquad [3.1]$$

Where,

P	Atmospheric pressure (kPa)
Z	Elevation above sea level (m), obtained from Google earth

3.4.2.2. Determination of Psychrometric Constant (γ)

The psychrometric constant together with the saturation vapour pressure curve are used to quantify the proportional term in Priestley-Taylor model, (equation 2.9). The psychrometric constant was computed as follows:

$$\gamma = \frac{C_p P}{\varepsilon\lambda} = 0.665 \text{ x } 10^{-3} \text{ P} \qquad [3.2]$$

Where,

γ	Psychrometric constant (kPa °C^{-1})
P	Atmospheric pressure (kPa)
λ	Latent heat of vaporization, 2.45 (MJ kg^{-1})
Cp	Specific heat at constant pressure, 1.013 x 10^{-3} (MJ kg^{-1} °C^{-1})
ε	Ratio molecular weight of water vapour/dry air (0.622)

3.4.2.3. Estimation of Slope of Saturation Vapour Pressure Curve (Δ)

The slope of saturation vapour pressure curve, Δ gives the relationship between saturation vapour pressure and air temperature. It was estimated as follows:

$$\Delta = \frac{4098[(0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right)]}{(T + 237.3)^2} \qquad [3.3]$$

Where,

Δ	Slope of saturation vapour pressure curve at air temperature T, (kPa °C^{-1})
T	Air temperature (°C)

3.4.2.4. Determination of Greenhouse Air Temperature

The mean air temperature inside the greenhouse, T_{mean} is defined as the mean of the daily maximum (T_{max}) and minimum temperatures (T_{min}) rather than as the average of hourly temperature measurements as follows:

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \qquad [3.4]$$

3. 4.2.5. Estimation of Relative Humidity

The relative humidity (RH) expresses the degree of saturation of the air as a ratio of the actual (e_a) to the saturation (e_s) vapour pressure at the same temperature. RH was estimated as follows:

$$RH = 100\frac{e_a}{e_s} \qquad [3.5]$$

3.4.2.6. Estimation of Mean Saturation Vapour Pressure (e_s)

Since saturation vapour pressure is related to air temperature, it can be estimated from the air temperature as follows:

$$e^o(T) = 0.6108 \exp\left(\frac{17.27T}{T+237.3}\right) \qquad [3.6]$$

Where,

e°(T)	Saturation vapour pressure at the air temperature T (kPa)
T	Air temperature (°C)

Air temperature was the average of the greenhouse air temperature measured at 9 am, 12 pm and 3 pm respectively.

3.4.2.7. Estimation of Actual Vapour Pressure (e_a)

The actual vapour pressure was derived from dew point temperature as follows:

$$e_a = e^o(T_{dew}) = 0.6108 \exp\left[\frac{17.27T_{dew}}{T_{dew} + 237.3}\right] \qquad [3.7]$$

Where,

T_{dew} Dew point temperature

Dew point is the temperature at which water vapour starts to condense out of the air (the temperature at which air becomes completely saturated) and for this study it was estimated from the pychrometric chart (Nautica Dehumidifiers) for given average wet bulb and dry bulb temperatures.

3.4.2.8. Determination of Vapour Pressure Deficit (e_s – e_a)

Vapour pressure deficit (VPD) is a valuable way of measuring greenhouse climate because it can be used to evaluate the disease threat, condensation potential and irrigation needs of a greenhouse crop. The vapour pressure deficit was determined as the difference between the saturation (e_s) and actual vapour pressure (e_a) for a given time period.

3.4.2.9. Estimation of Net Radiation (Rn)

Net radiation (R_n) can be measured but such data are seldom available. Instead, it is calculated from solar radiation on sunshine hours, temperature, and humidity data. R_n was computed as the algebraic sum of the net shortwave radiation (R_{ns}) and net longwave radiation (R_{nl}) as shown in equation (3.8).

$$\mathrm{Rn} = [(1 - \alpha)\mathrm{Rs} - \mathrm{Rln}] \qquad [3.8]$$

Where,

R_n	Net radiation energy ($MJm^{-2}day^{-1}$)
α	Albedo whose value of 0.23 for green crop
R_s	Solar irradiance ($MJm^{-2}\ day^{-1}$)
R_{ln}	Net longwave (thermal) radiant energy ($MJm^{-2}day^{-1}$)

3.4.2.10. Estimation of Net Longwave Radiation Energy (R_{ln})

The rate of longwave energy emission is proportional to the absolute temperature of the surface raised to the fourth power and this is expressed quantitatively by the Stefan-Boltzmann law. The net longwave radiant energy was estimated as follows:

$$\mathrm{Rln} = \left[a\frac{\mathrm{Rs}}{\mathrm{Rso}} + b\right] \varepsilon' \sigma\,(T_m + 273)^4 \qquad [3.9]$$

Where,

R_{so}	Daily clear day irradiance ($MJm^{-2}\ day^{-1}$)
a and b	Empirical coefficient
ε'	Net emissivity

σ	Stefan – Boltzmann Constant = 4.896 x 10^{-9} ($MJm^{-2}day^{-1}K^{-4}$)
Tm	Daily mean temperature (^oC)

R_{so} was calculated using equation (3.10) as show below:

$$Rso = 22.357 + 11.0947 \cos D - 2.3594 \sin D \qquad [3.10]$$

Where,

$$D = \frac{DOY}{365.25 \text{ x } 2\pi} \qquad [3.11]$$

Meyer (1999) proposed the relationship between the empirical coefficients a and b as follows:

$$\left[a\frac{Rs}{Rso} + b\right] = 1 \qquad [3.12]$$

Meyer (1999) proposed empirical values for the constants a and b as 0.92 and 0.08 respectively. From equation (3.12), when the sum of a and b is 1, then $R_s = R_{so}$ and equation (3.9) reduces to:

$$Rln = \varepsilon'\sigma(Tm + 273)^4 \qquad [3.13]$$

Meyer (1999) proposed equation (3.14) for calculating net emissivity as:

$$\varepsilon' = c + d\sqrt{e_d} \qquad [3.14]$$

Where,

c and d	Empirical constants whose values are 0.34 and – 0.139 respectively

e_d Vapour pressure at mean daily dew point temperature (kPa)

3.5. Estimation of Crop Water Requirement and Applied Irrigation Water

3.5.1. Crop Water Requirement

In this study, the experiment was carried out during the crop development, middle and late growth stages and therefore, the crop coefficient (Kc) values used as recommended by FAO (1986) were 0.75, 1.15 and 0.75 respectively. The water requirement of tomato crop per plant per day under drip irrigation was computed using equation 3.15 (Dunage *et al*., 2009; Sharan and Jadhav, n.d).

$$Q = A \times B \times C \times D \qquad [3.15]$$

Where,

Q Quantity of water required per plant (litres $plant^{-1}$ day^{-1})

A Gross area per plant (m^2)

B Amount of area covered with foliage (fraction)

C Crop coefficient (fraction)

D Reference evapotranspiration, ETo (mm)

Gross area per plant was calculated from the spacing of the crop (Sharan and Jadhav, n.d). The amount of area covered with foliage was assumed to vary from 0.5 to 0.85 from initial to full maturity stages of crop growth respectively. A similar study by Harmanto *et al.* (2005) proposed the following values of shading by plant canopy: initial stage; 0.5 - 0.6, development stage; 0.6 - 0.8, mid stage; 0.8 - 0.85, late stage; 0.85 - 0.8. These values were adopted for this study.

3.5.2. Applied Irrigation Water

Overall irrigation efficiencies of 85 and 90 % were assumed for all the treatments in the calculation of irrigation requirement at Matinyani and Kyondoni greenhouses respectively. This assumption was arrived at on the basis that the system at Matinyani had been previously used while the one at Kyondoni had not. The irrigation water requirement per plant per treatment was computed using the following equation:

$$\mathrm{IWR} = \frac{\mathrm{Q} * \mathrm{k}}{\eta} \qquad [3.16]$$

Where,

IWR	Irrigation water requirement per plant (litres plant^{-1})
Q	Tomato water requirement per plant (litres plant^{-1} day^{-1})
η	Irrigation efficiency (%)
k	Selected adjustment coefficient per treatment

Each drip lateral in every treatment was fitted with a mini valve (figure 3.5) in order to control the irrigation amount. The exact amount of irrigation water per treatment was administered by carefully taking the reading of the flow meter (flow rate 4 m^3h^{-1}) installed along the sub-main (figure 3.6).

Figure 3.5: A Fitted mini-valve **Figure 3.6: Installed water meter**

3.6. Physiological Measurements and Harvesting

The main physiological measurements carried out on tomato plants were plant height, stem diameter, fruit diameter and fruit weight. These physiological measurements were carried out on identified plants from each treatment. The measurements of plant height and stem diameter were carried out every week during the growth stages of the crop while fruit weight and diameter were done during harvesting. The stem and fruit diameters were measured physically using a vernier caliper (figures 3.7 and 3.8).

Figure 3.7: Measuring stem diameter **Figure 3.8: Measuring fruit diameter**

The plant height was determined by measuring the length of the plant from the base to the apex of the plant using a tape measure (figure 3.9). An electronic balance with a sensitivity of 0.001 g (type, twins JY09) was used to obtain the weight of identified tomato fruits (figure 3.10).

Figure 3.9: Measuring plant height **Figure 3.10: Measuring fruit weight**

Physiological measurements were recorded with pen and paper and later input into a spreadsheet in Microsoft Excel for processing.

Tomato fruits were harvested manually from 70 to 80 days after transplanting. The fruits produced were weighed using an electronic balance (Sartorius) with an accuracy of ±0.01 g. Yield in kilograms was converted to equivalent yield in kilograms per square metre of each treatment bed using equation (3.17).

$$\text{Yield (kg m}^{-2}\text{)} = \frac{\text{Yield per Treatment (kg)}}{\text{Area per treatment (m}^2\text{)}} \qquad [3.17]$$

The quality of tomatoes was also quantified by two parameters namely; fruit diameter and fruit weight.

3.7. Determination of Soil Properties

3.7.1. Soil Sampling

Soil sampling was carried out at the two greenhouse sites in order to investigate the following properties: particle size distribution, soil type, field capacity, permanent wilting point, bulk density and porosity. Disturbed and undisturbed soil samples were collected at three randomly selected sampling points and at three depth intervals: 0 – 20 cm, 20 – 40 cm and 40 – 60 cm respectively. Soil samples at Matinyani were collected from inside and outside the greenhouse because it had been installed a year earlier. This was done to establish whether soil properties had been affected by previous farming activities. At Kyondoni soil samples were taken at the greenhouse site during installation process.

3.7.2. Soil Analysis

Undisturbed soil samples were analyzed for field capacity, permanent wilting point and soil bulk density using the pressure plate apparatus method. The analysis was carried out at Kabete Soil and Water Laboratory, Department of Environmental and Biosystems Engineering, University of Nairobi. Dry bulk density was determined from three undisturbed soil samples for each depth interval using 5.5 cm-diameter and 4 cm-length core rings. A representative average bulk density was obtained for each depth interval and used to convert the mass water content determined by gravimetric analysis into volumetric water content. The field capacity and permanent wilting point were determined from the water retention characteristics of each soil depth.

Disturbed soil samples were analyzed for particle size distribution, soil aggregate stability, pH and salinity. The samples were air-dried and passed through a 2 mm sieve following which particle size distribution was determined using the hydrometer method while aggregate stability was determined using the wet sieving apparatus method. Soil pH and salinity were determined using soil pH meter and electrical conductivity meter respectively.

3.7.3. Soil Water Infiltration

The infiltration rate was measured using the double ring infiltrometer which consisted of an inner and outer ring inserted into the ground to a depth of around 5 cm. Each ring was supplied with a constant head of water manually. Data was gained by a drop in water height which gave infiltration of water over time. The rate of infiltration was then determined by the amount of water that infiltrated into the soil per surface area, per unit of time.

3.8. Determination of Soil Water Content and its Change in the Soil

In this study, soil water content was measured using gravimetric method at 0.3 m interval down to 0.6 m before irrigation. Soil samples were collected every week from each treatment at three sampling points using a soil auger. Holes caused by gravimetric sampling were subsequently refilled with soil and re-compacted to prevent preferential flow. The samples were oven dried at 105 ºC for 24 hours and weighed. The mass water content was computed using the following equation:

$$\theta_m = \frac{M_w}{M_s} \qquad [3.18]$$

Where,

θ_m	Mass water content ($g\ g^{-1}$)
M_w	Mass of water evaporated (g)
M_s	Mass of dry soil (g)

The mass water content was converted to volumetric water content (θ_v) which represented the volume of water contained in a volume of soil and was computed using the following equation:

$$\theta_v = \frac{\rho_b}{\rho_w}\theta_m \quad [3.19]$$

Where,

θ_v	Volumetric water content ($cm^3\ cm^{-3}$)
ρ_w	Soil bulk density ($g\ cm^{-3}$)
ρ_b	Density of water ($1\ g\ cm^{-3}$)
θ_m	Mass water content ($g\ g^{-1}$)

The relationship between volumetric water content and the equivalent depth of water in a soil layer was represented by the following equation:

$$d = \theta_v L \quad [3.20]$$

Where,

d	Equivalent depth of water in a soil layer (mm)
L	Depth increment of the soil layer (mm)

The change in soil water content for the measured depths was determined by subtracting the final soil water content at the end of the duration of the study from the initial soil water content at the beginning of monitoring (Fernandez *et al*., 2010) in each treatment as shown in equation (3.21).

$$\Delta SM = SM_i - SM_f \quad [3.21]$$

Where

ΔSM	Change in soil water content (mm)
SM_i	Total profile soil water depth at the starting of the time period considered (mm)
SM_f	Total profile soil water depth at the ending of the time period considered (mm)

The total change in soil water content in each treatment was computed as the sum of change of soil water contents for the two sampling depths .i.e. 0-30 cm and 30-60 cm.

3.9. Actual Crop Evapotranspiration

Actual crop evapotranspiration was computed using the soil water balance equation (discussed in chapter two, equation 2.15). This balance did not consider surface runoff because drip irrigation system was used. In addition, due to the small variation in soil water contents below 30 cm depth, deep percolation was considered negligible. Therefore, actual crop evapotranspiration was computed using equation (2.16).

The equivalent depth of the applied irrigation water for each treatment was computed as the ratio of the total volume of applied irrigation water per plant to the effective irrigated area per plant (Arku *et al*., 2012).

3.10. Irrigation Water Productivity (IWP)

Harmanto *et al*. (2005) stated that irrigation water productivity (IWP) represents the productivity of irrigation water related to the crop yield. Water productivity in crop production is clarified by use of the terms WUE and IWUE (Bozkurt and Mansuroglu, 2011; Harmanto *et al*., 2005). Water use efficiency (WUE, kg m^{-3}) and irrigation water use efficiency (IWUE, kg m^{-3}) were computed using equations (3.22) and (3.23) (Sezen *et al*., 2006).

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ETc}} \qquad [3.22]$$

$$\mathrm{IWUE} = \frac{\mathrm{Y}}{\mathrm{I}} \qquad [3.23]$$

Where,

Y	Crop yield (kg m^{-2})
ETc	Crop evapotranspiration (mm)
I	Applied irrigation water (mm)

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1. Soil Characterization

Table 4.1 presents the particle size distribution, soil type, field capacity, permanent wilting point, bulk density and porosity of the soils at the experimental sites. The soils are classified as sandy clay loam at Matinyani and sandy clay at Kyondoni. At Matinyani, the sand content decreased with depth while the clay content increased. This trend was attributed to the previous farming activities which could have caused dispersion of the clay particles. At Kyondoni, it was noted that the sand and clay contents at 20 – 40 cm depth were higher than at the depths 0 – 20 cm and 40 – 60 cm. Further, it was also noted that the sand contents at 0-20 cm and 20-40 cm depths remained the same while the clay contents were nearly the same. These trends were attributed to the natural characteristics of the soil formation.

The soil bulk density indicated a gradual increase with depth down the profile in the experimental sites. The results indicated that bulk density of the soil at Matinyani was higher than at Kyondoni. Basically, soil bulk density is an indicator of soil compaction and soil health because it affects infiltration, available water capacity, rooting depth/restrictions, plant nutrient availability, soil porosity, and soil microorganism activity which influence key soil processes and productivity (Andreu *et al*., 1997). The high bulk densities also explain the general absence of roots below the 0.6 m soil depth and this symbolized that the soil was very compact (Andreu *et al*., 1997). In this regard therefore, it could be inferred that the difference in the soil properties at the two sites could have slightly affected the crop growth parameters, yield and soil water balance.

Field capacity and permanent wilting point values at Kyondoni decreased with depth but this was not the trend with the same at Matinyani. Further, FC and PWP values at Kyondoni were higher than those at Matinyani. The indication was that the soil at Kyondoni had a higher value of available water content (AWC) compared to the soil at Matinyani. This too could have affected crop growth parameters, yield and soil water content. It was also noted that FC and PWP values at 0 - 20 cm depth at Matinyani (inside and outside the greenhouse) were lower than those for the other depths. This was attributed to land preparation activities and possibly due to the effect of the organic matter incorporated into the soil at Matinyani where farming had been practiced earlier.

It was noted that the soil at Kyondoni had a higher porosity than at Matinyani. This was attributed to the high contents of clay and silt in the soil which could have led to the increase in the number of pores in the soil. Normally, clay particles are somewhat flexible and plastic in nature because of their lattice-like design. This special feature allows clay particles to absorb water and other substances into their structure. This also explains the high values of soil FC and PWP at Kyondoni.

Table 4.1: Soil Properties in the Greenhouses under Experiment

Greenhouse	Soil depth (cm)	Sand (%)	Clay (%)	Silt (%)	Soil type	FC (%)	PWP (%)	BD (g cm^{-3})	Porosity (%)
Kyondoni	0 – 20	50.44	37.95	11.61	SC	20.00	14.71	1.21	54.34
	20 – 40	52.44	40.61	6.95	SC	19.47	13.58	1.26	52.45
	40 – 60	50.44	37.28	12.28	SC	14.95	12.94	1.27	52.08
Matinyani (I)	0 – 20	69.69	24.38	5.93	SCL	11.90	8.02	1.14	56.98
	20 – 40	62.03	32.05	5.93	SCL	13.90	10.67	1.42	46.42
	40 – 60	61.36	33.05	5.59	SCL	13.41	10.26	1.43	46.04
Matinyani (O)	0 – 20	71.27	21.47	7.05	SCL	12.09	8.80	1.26	52.45
	20 – 40	65.27	27.47	7.26	SCL	12.61	9.48	1.35	49.06
	40 – 60	63.27	31.14	5.59	SCL	12.34	9.42	1.47	44.53

Key: SC = Sandy Clay; SCL = Sandy Clay Loam; FC = Field Capacity; PWP = Permanent Wilting Point; BD = Bulk Density; I = Inside; O = Outside

Table 4.2 summarizes the pH and electrical conductivity values of the soils at the experimental sites. These results indicated that the pH of the soil at Matinyani was higher than at Kyondoni while electrical conductivity was vice versa. This was attributed to the effect of farming activities previously carried out within Matinyani greenhouse. The soil pH at both sites was within the range of 6.5 to 7.5 whose reaction is regarded neutral for irrigation purposes and has maximum availability of all the essential plant nutrients. It was noted that soil pH was higher at surface level as compared to subsurface level. This was attributed to the accumulation of salts resulting from evaporation process at the surface level.

The electrical conductivity of the soil at Kyondoni increased with depth and decreased with depth at Matinyani. This was attributed to the effect of irrigation previously carried out at Matinyani which led to accumulation of salts at the surface level. The electrical conductivity values were less than 0.7 and therefore the soils were classified as non-saline and hence suitable for crop production.

Table 4.2: Variation of Soil pH and electrical conductivity with depth

Greenhouse	Level	Ec (dS m^{-1})	pH
Kyondoni	Surface (0 – 30 cm)	0.45	6.72
	Subsurface (30 - 60 cm)	0.60	6.60
Matinyani	Surface (0 – 60 cm)	0.40	7.40
	Subsurface (30 - 60 cm)	0.30	7.01

Table 4.3 presents the average soil aggregate stability within the experimental sites. The results indicated that the average soil aggregate stability was higher at Matinyani as compared to Kyondoni. This was attributed to the fact that the clay content at Kyondoni was higher and this could have led to more particle dispersion. The results for Matinyani indicated that average soil aggregate stability decreased with depth except for the depth (20 – 40 cm) inside the greenhouse. This was attributed to the reduction in the cohesive forces between the soil particles as the depth increased.

The high values of soil aggregate stability at both experimental sites were an indication of stable aggregates which could have provided a large range in pore space, including small pores within and large pores between aggregates. Pore space is essential for air and water entry into soil, and for air, water, nutrient, and biota movement within soil.

Table 4.3: Variation of soil aggregate stability with depth

Location	Soil depth (cm)	Before dispersing (%)	After dispersing (%)
Kyondoni	0 – 20	98.33	85.70
	20 – 40	97.33	84.10
	40 – 60	96.75	80.88
Matinyani (Inside)	0 – 20	99.67	88.17
	20 – 40	98.67	90.05
	40 – 60	98.08	85.63
Matinyani (Outside)	0 – 20	99.40	88.40
	20 – 40	98.90	88.11
	40 – 60	97.90	86.66

The soil infiltration rates were 6.0 cm/hr and 7.3 cm/hr at Kyondoni and Matinyani respectively. The high infiltration rate at Matinyani was attributed to the changes in the soil structure resulting from previous farming activities which could have made the soil to be loose. Moreover, soils at Matinyani had a higher percentage of sand compared to the ones at Kyondoni and generally sandy soils have higher infiltration rates.

4.2. Greenhouse Microclimate

The greenhouse microclimate was summarized in tables 4.5 and 4.6 for the periods between July and September 2013 and August to October 2013 for Matinyani and Kyondoni respectively.

Table 4.4: Summary of greenhouse microclimate within Matinyani greenhouse

	Air Temperature (^oC)			Relative Humidity (%)			Net Radiation Energy (MJ m^{-2} day^{-1})		
Month	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
July	9.50	36.80	21.97	47.35	87.15	62.80	20.21	22.29	20.92
August	9.50	38.60	21.59	48.63	89.48	68.53	20.36	21.80	21.18
September	9.50	35.00	22.52	50.37	67.75	58.00	20.76	21.86	20.27

Table 4.5: Summary of greenhouse microclimate within Kyondoni greenhouse

	Air Temperature (^oC)			Relative Humidity (%)			Net Radiation Energy (MJ m^{-2} day^{-1})		
Month	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
August	9.50	31.50	20.29	49.62	75.97	63.62	19.87	21.43	20.40
September	9.00	30.00	19.55	54.89	71.74	63.01	20.34	21.31	20.74
October	11.00	31.50	20.19	56.57	73.81	63.94	20.02	21.43	20.77

4.2.1. Relative Humidity

At Kyondoni, the minimum and maximum relative humidity values within the greenhouse were 49.62 % and 75.97 % reached on DOY 237 and 243 respectively. The average daily relative humidity for the month in August, September and October respectively were 63.62 %, 63.01 % and 63.94 % while the average for the duration of the study was 63.48 %. The results showed that October was a relatively more humid month and this was attributed to the stable temperatures recorded within the greenhouse in the month (figure 4.1).

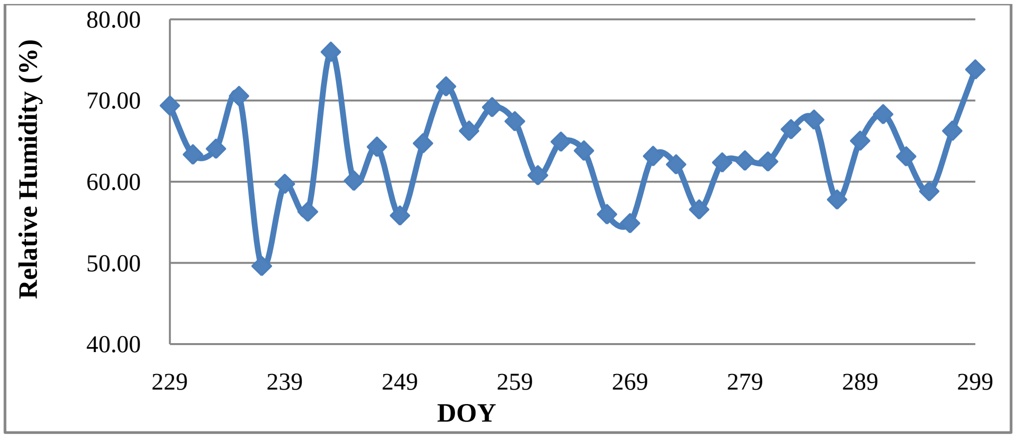

Figure 4.1: Variation of relative humidity within Kyondoni greenhouse (17th August, 2013 = DOY 229)

Relative humidity within the greenhouse at Matinyani was very unstable (figure 4.2). A pattern of high and low relative humidity levels was observed and this was due to the unstable temperatures recorded within the greenhouse. However, relative humidity was slightly stable from DOY 235 up to the end of the experiment (DOY 258) and this was an indication that air temperature within the greenhouse had also stabilized. The minimum and maximum relative humidity levels were 47.35 % and 89.48 % reached on DOY 212 and 221 respectively. The average daily relative humidity levels for the months in July, August and September were 65.79 %, 68.53 % and 58.00 % respectively while the mean average value for the duration of the study was 64.10 %. At Matinyani, the month of August was relatively more humid and this was possibly due to the fact that it was also a cooler month.

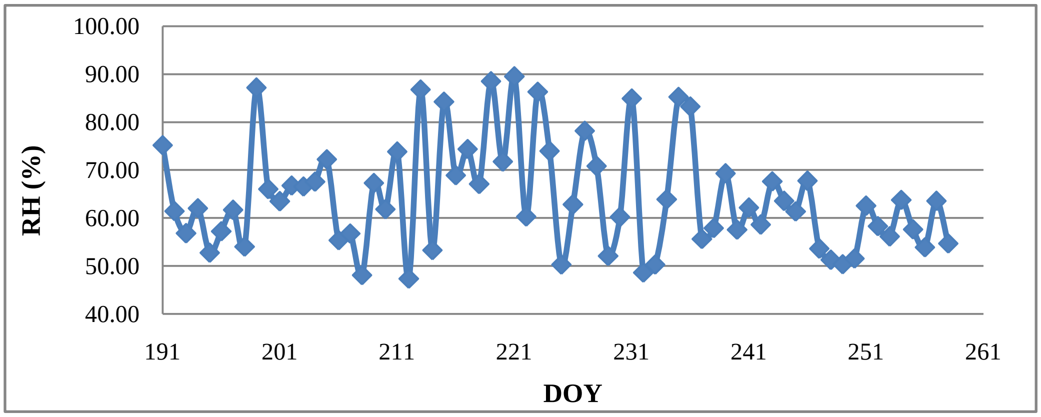

Figure 4.2: Variation of relative humidity within Matinyani greenhouse (10th July, 2013 = DOY 191)

4.2.2. Greenhouse Air Temperature

Figure 4.3 shows the variation of minimum, maximum and mean air temperature within the greenhouse at Kyondoni. The minimum and maximum air temperatures were 9 ^{o}C and 31 ^{o}C reached on DOY 265 and 293 respectively while the average minimum and maximum air temperatures for the duration of the study were 11.57 ^{o}C and 28.81 ^{o}C respectively. The mean air temperature inside the greenhouse varied gradually throughout the duration of the study and its average value was 20.19 ^{o}C. The optimum range in air temperature best suited for normal tomato plant growth is between 18 °C and 26 °C (Hendricks, 2012). This value was within the design temperature range for tomato crop grown inside a greenhouse hence it was regarded safe for tomato growth (Hendricks, 2012; Popovski, 1997; Vox *et al.*, 2010).

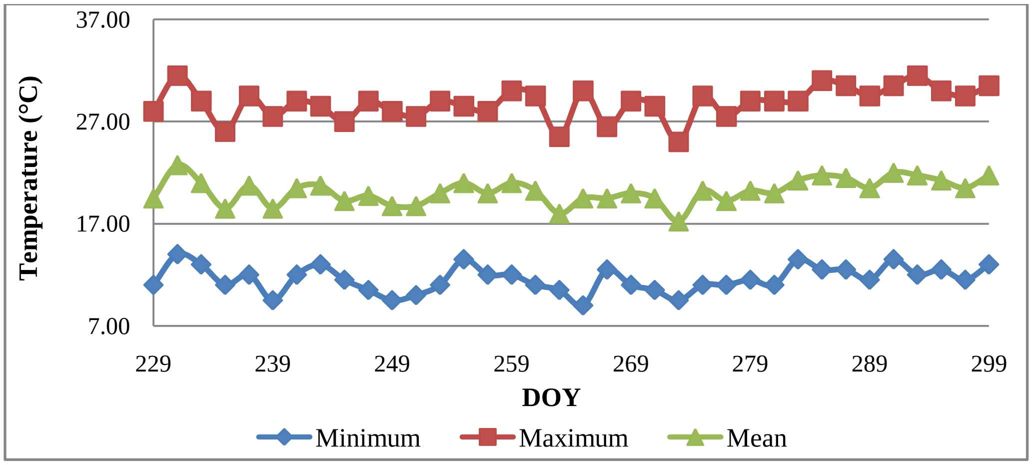

Figure 4.3: Variation of minimum, maximum and mean air temperature within Kyondoni greenhouse

Figure 4.4 shows the variation of minimum, maximum and mean air temperatures within the greenhouse at Matinyani. The figure shows that air temperature had a high variability between DOY 206 and 216 and reached a maximum of 35.80 °C on DOY 208. Further, from DOY 216 up to DOY 249, the variability increased reaching a maximum of 38.60 °C on DOY 226 and a minimum of 9.50 °C on DOY 244. However, from DOY 249 up to the end of the experiment, temperature stabilized and variability was very minimal.

The average minimum, maximum and mean greenhouse air temperatures throughout the study period were 11.90 ° C, 31.93 °C and 21.92 °C respectively. Although the mean greenhouse air temperature was fairly high, it was below the threshold regarded as dangerous to crop growth (Hendricks, 2012; Popovski, 1997; Vox *et al.*, 2010). The results of the experiment confirm that air temperature inside the greenhouse is fairly high (Grey, 2010). Air temperatures in the greenhouse lead to higher saturation vapour pressure and while a low relative humidity means low actual vapour pressure inside the greenhouse thus leading to a high vapour pressure deficit (Grey, 2010).

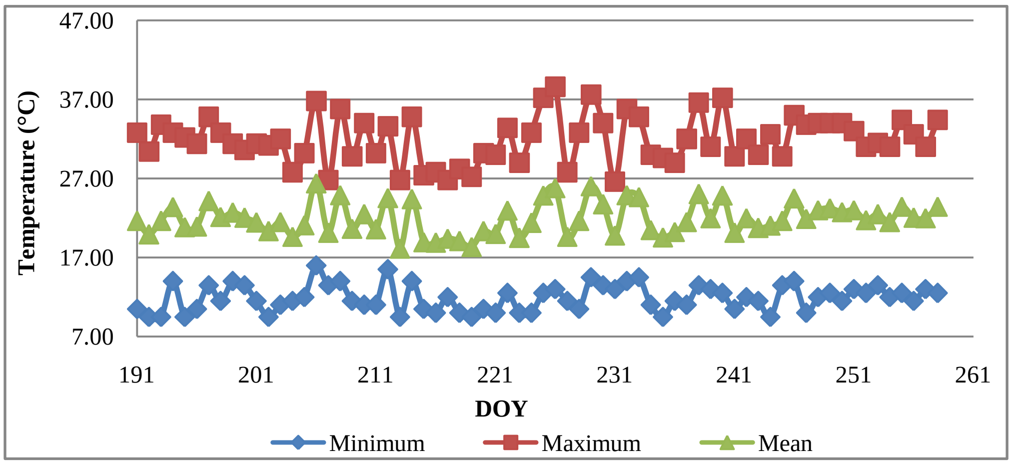

Figure 4.4: Minimum, maximum and mean greenhouse air temperature within Matinyani greenhouse

4.2.3. Dry Bulb, Wet and Dew Point Temperature

Figure 4.5 shows the variation of dry bulb, wet and dew point temperatures within the greenhouse at Kyondoni. The means of the average wet bulb and dry bulb temperature for the duration of the study were 20.87 ^{o}C and 25.88 ^{o}C respectively. It was observed that high variability between dry bulb and wet bulb temperatures led to lower humidity levels while slight variations resulted to slightly higher levels. However, low relative humidity levels were recorded because dew point temperature remained far below the dry air temperature.

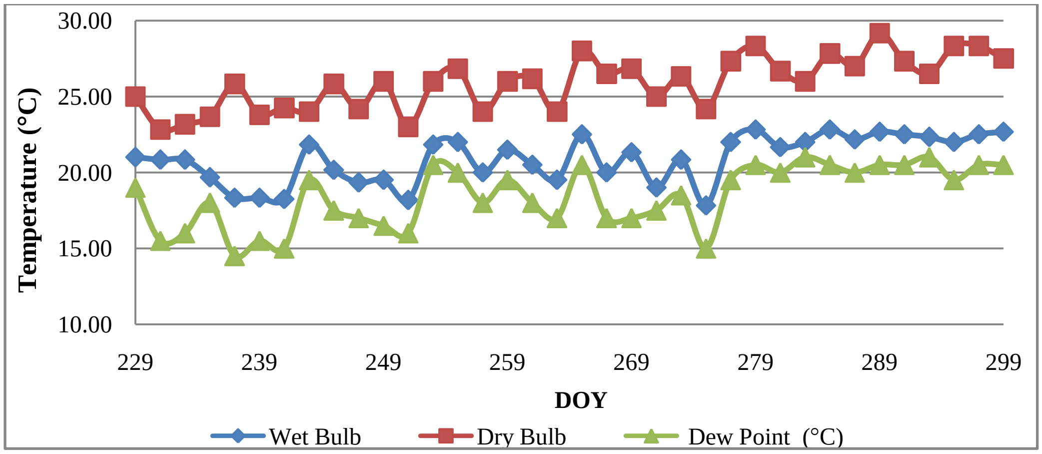

Figure 4.5: Variation of average dry bulb, average wet bulb and dew point temperatures within Kyondoni greenhouse

The variation of average dry bulb, average wet bulb and dew point temperatures within the greenhouse at Matinyani are shown in figure 4.6. According to the figure, dry bulb temperature remained fairly high throughout the experiment. The average minimum and maximum average dry bulb temperatures were 23.33 ^{o}C and 32.67 ^{o}C reached on DOY 221 and 249 respectively while the mean average value for the study period was 28.00 ^{o}C.

On the same note, the average wet bulb temperatures remained fairly stable throughout experiment. In this regard, the mean value for the study period was 22.90 ^{o}C while the minimum and maximum average values were 19.67 ^{o}C and 27.47 ^{o}C reached on DOY 234 and 240 respectively. The variation of dry bulb temperatures throughout the experiment led to variation of dew point temperature and as a consequence this led to varying values of relative humidity levels.

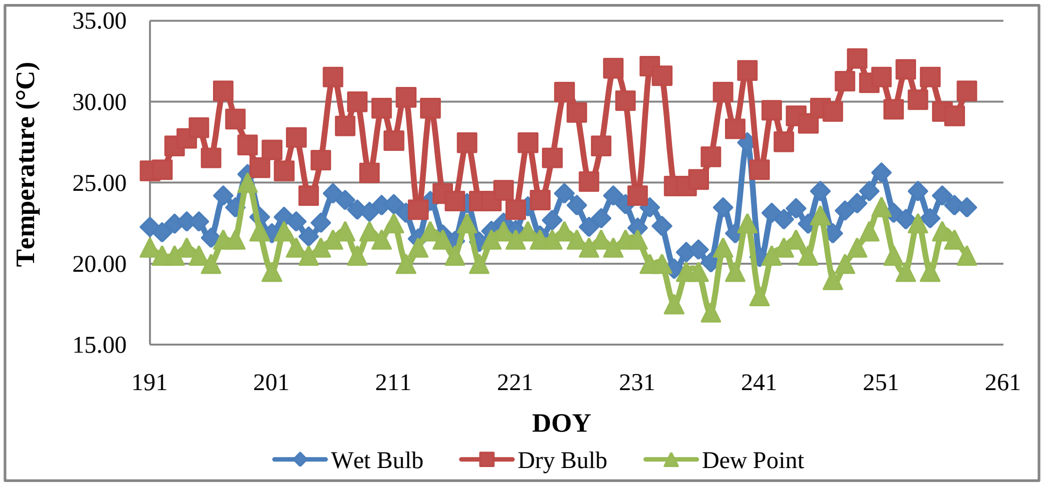

Figure 4.6: Variation of dry, wet and dew point temperature within Matinyani greenhouse

4.2.4. Saturation and Actual Vapour Pressure

Figure 4.7 shows the variation of saturation and actual vapour pressures within the greenhouse at Kyondoni. The minimum and maximum values of saturation vapour pressure were 2.7807 and 4.0452 kPa reached on DOY 231 and 287 respectively while the minimum and maximum actual vapour pressures were 1.612 and 2.487 kPa reached on DOY 237 and 283 respectively. The mean saturation and actual vapour pressure values for the duration of the study were 3.3562 and 2.1269 kPa respectively.

It was noted that the saturation and actual vapour pressures within the greenhouse increased with rise in air and dew point temperatures respectively. Saturation vapour pressure within the greenhouse was slightly high and this was an indication that the air within the greenhouse was fairly saturated.

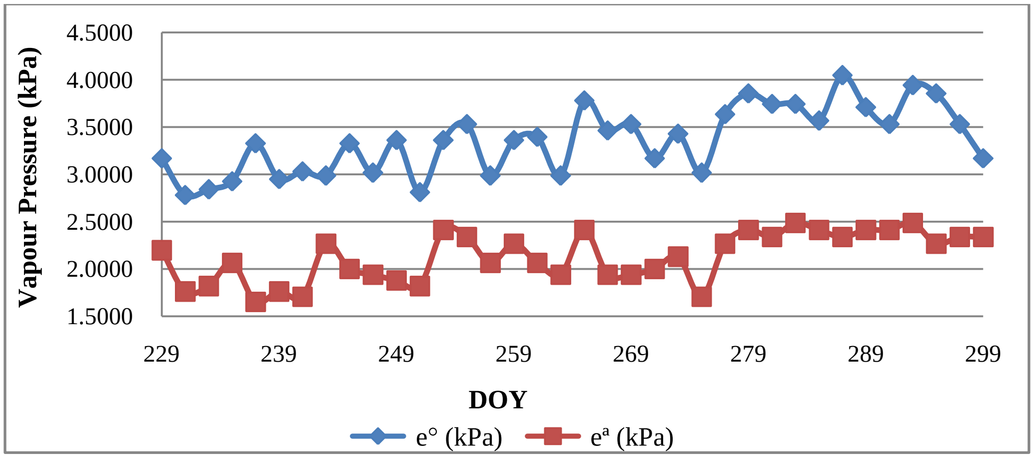

Figure 4.7: Variation of saturation and actual vapour pressure within Kyondoni greenhouse

Figure 4.8 shows the variation of saturation and actual vapour pressures within the greenhouse at Matinyani. According to the figure, the fluctuation of saturation vapour pressure was higher compared to the actual vapour pressure. The minimum and maximum saturation vapour pressure values were 2.8660 and 4.9378 kPa reached on DOY 221 and 229 respectively while the minimum and maximum actual vapour pressure values were 1.9377 and 3.1678 kPa reached on DOY 237 and 199 respectively.

It was noted that saturation vapour pressure was very high due to the high air temperatures recorded within the greenhouse (Grey, 2010). However, actual vapour pressure values were lower than saturation vapour pressure and this was an indication that there existed a high vapour pressure differential within the greenhouse.

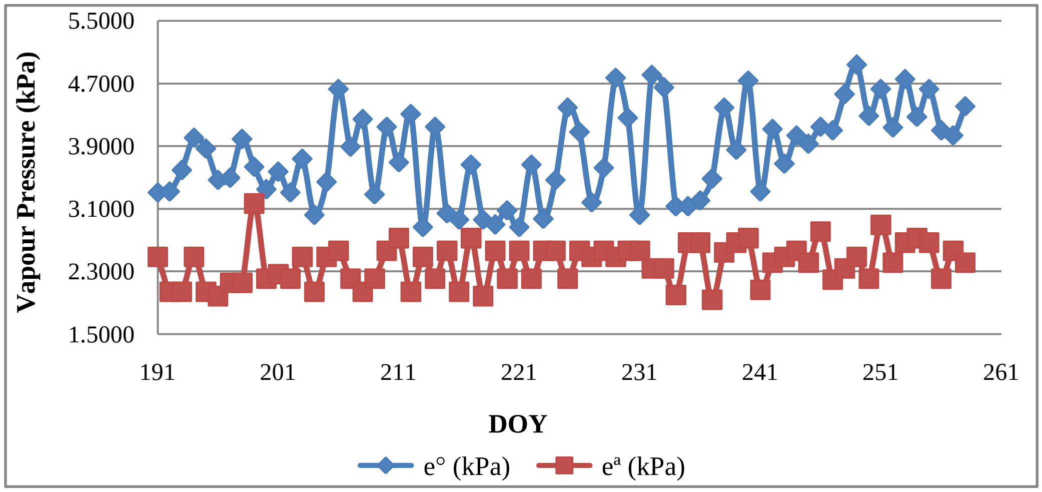

Figure 4.8: Variation of saturation and actual vapour pressure within Matinyani greenhouse

4.2.5. Vapour Pressure Deficit (VPD)

Figure 4.9 shows the variation of mean vapour pressure deficit within the greenhouse at Kyondoni. The minimum and maximum VPD values were 0.8296 and 1.707 kPa reached on DOY 299 and 287 respectively while the mean value for the duration of the study was 1.229 kPa. Pathogens survive best at VPD less than 0.43 kPa and since the mean VPD for the duration of the study was above this value, it was therefore concluded that the greenhouse was probably free from fungal attack.

Sabeh (2007) stated that VPD is the major component which drives evapotranspiration because it drives moisture from the plant into the air and as such the two have an indirect relationship. At Kyondoni, VPD remained fairly high throughout the experiment and this was an indication that the transpirational demand was also fairly high.

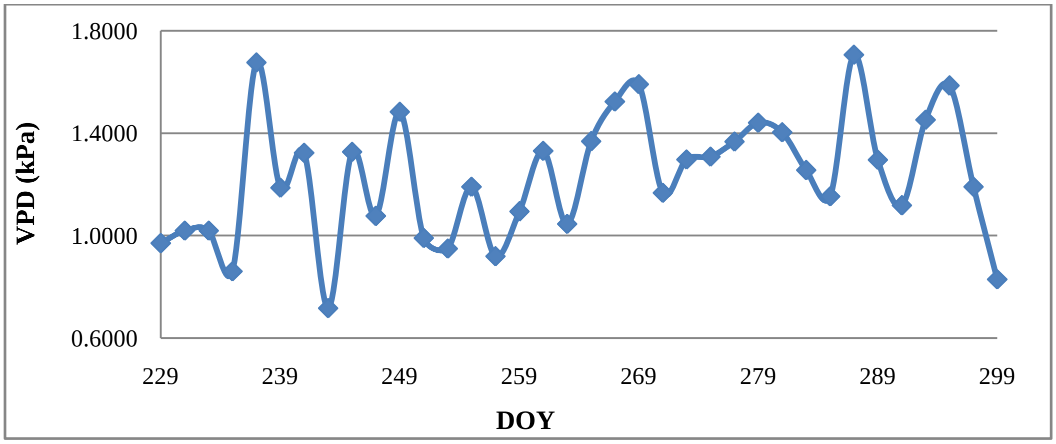

Figure 4.9: Variation of vapour pressure deficit within Kyondoni greenhouse

Figure 4.10 shows the variability of VPD within the greenhouse at Matinyani. The figure shows that the variation of VPD within the greenhouse was very high especially in the month of August. This variability depicted a fluctuating trend of evapotranspiration within the greenhouse. The minimum and maximum VPD values were 0.3016 and 2.4705 kPa reached on DOY 221 and 232 respectively while the mean value for the duration of the study was 1.4016 kPa. The minimum value of VPD for the duration of the study was below the threshold value and this indicated that the greenhouse had a likelihood of attack from fungal diseases. Generally, VPD remained high for a greater number of days during the experiment and this was an indication that transpirational demand was quite high.

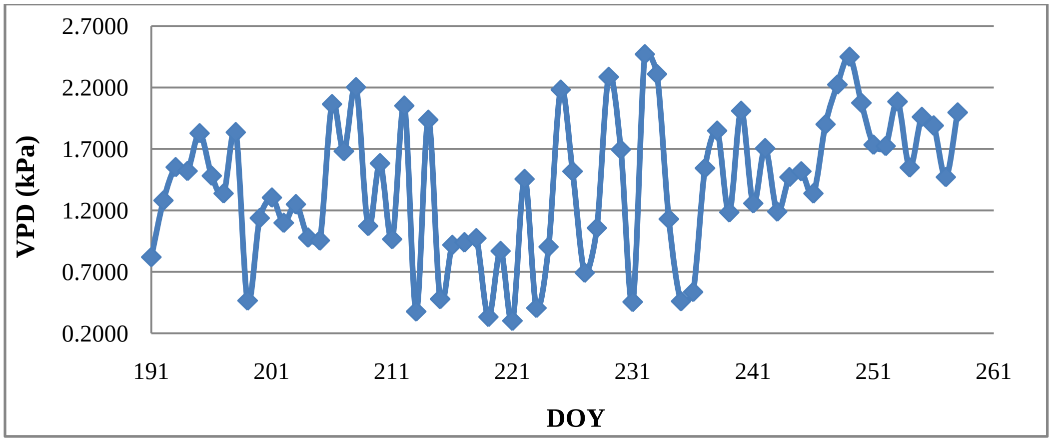

Figure 4.10: Variation of vapour pressure deficit within Matinyani greenhouse

4.2.6. The Slope of Saturation Vapour Pressure Curve

Figure 4.11 shows that the variations of the slope of saturation vapour pressure curve within the greenhouse at Kyondoni. According to the figure, the slope was fairly stable throughout the experiment and this was attributed to the slight variation in the greenhouse air temperature. It was noted that the slope of saturation vapour pressure curve increased with the increase in air temperature. The average greenhouse air temperature varied between 23 and 30 ^{o}C, this was an indication that the vaporization activity within the greenhouse was also average. The minimum and maximum slope values were 0.1684 and 0.2335 kPa $^{o}C^{-1}$ reached on DOY 231 and 287 respectively while mean value for the duration of the study was 0.1982 kPa $^{o}C^{-1}$.

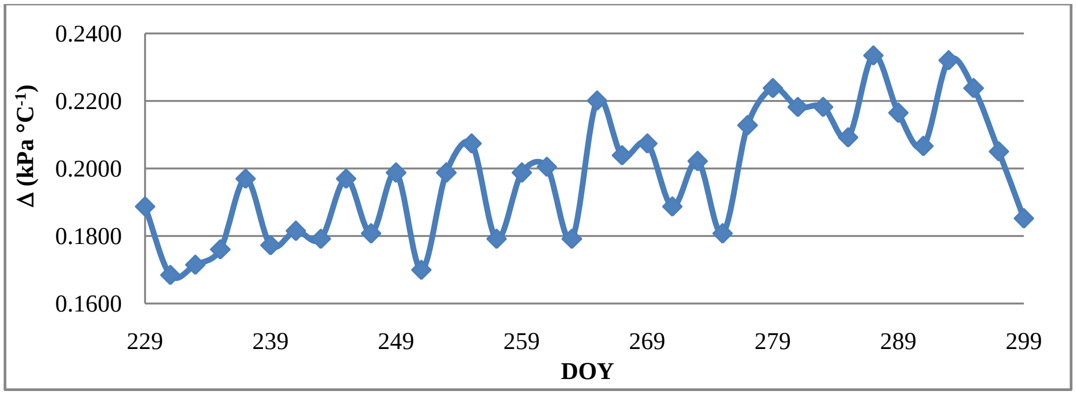

Figure 4.11: Variation of slope of saturation vapour pressure curve within Kyondoni greenhouse

Figure 4.12 shows the variation of slope of saturation vapour pressure curve within the greenhouse at Matinyani. According to the figure, the value of the slope showed very high variability throughout the experiment especially between DOY 206 and 241. The minimum and maximum values were 0.1729 and 0.2776 $kPa^{o}C^{-1}$ reached on DOY 221 and 249 respectively while the mean value for the study period was 0.2209 $kPa^{o}C^{-1}$. The value of the slope remained quite high throughout the experiment and this was an indication that vaporization activity within the greenhouse was quite high.

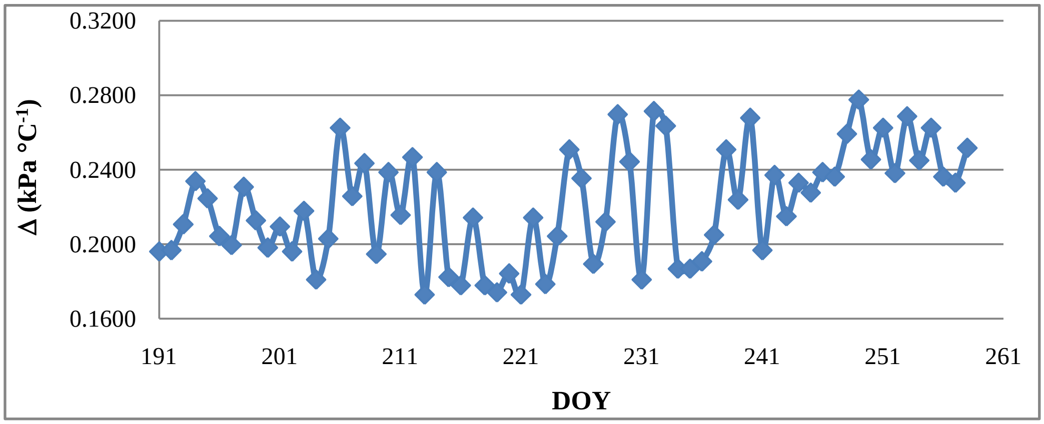

Figure 4.12: Variation of slope of saturation vapour pressure curve within Matinyani greenhouse

4.2.7. Soil Temperature

The minimum and maximum soil temperatures inside the greenhouses were observed at 9.00 am and 3.00 pm respectively. The rise in soil temperature between 9.00 am and 3.00 pm was attributed to the rise in the air temperature within the greenhouse. The variation of soil temperature inside the greenhouse at Kyondoni is shown in figure 4.13. The figure shows that soil temperature was high in the month of August especially at 12.00 noon and 3.00 pm. The minimum and maximum soil temperatures were 20.20 ^{o}C and 27.60 ^{o}C reached on DOY 229 and 260 respectively while the mean values for the duration of the study were 21.22, 23.07 and 24.42 at 9 am, 12 pm and 3 pm respectively. Popovski (1997) reported that under strong light intensity, the optimal soil temperatures for tomato crop during flowering and harvesting stages range between 19 - 22 ^{o}C and 23 - 25 ^{o}C respectively. In connection with this, the average soil temperature for the duration of the study was within this range hence flowering and harvesting stages for the crop were probably not affected (Popovski, 1997).

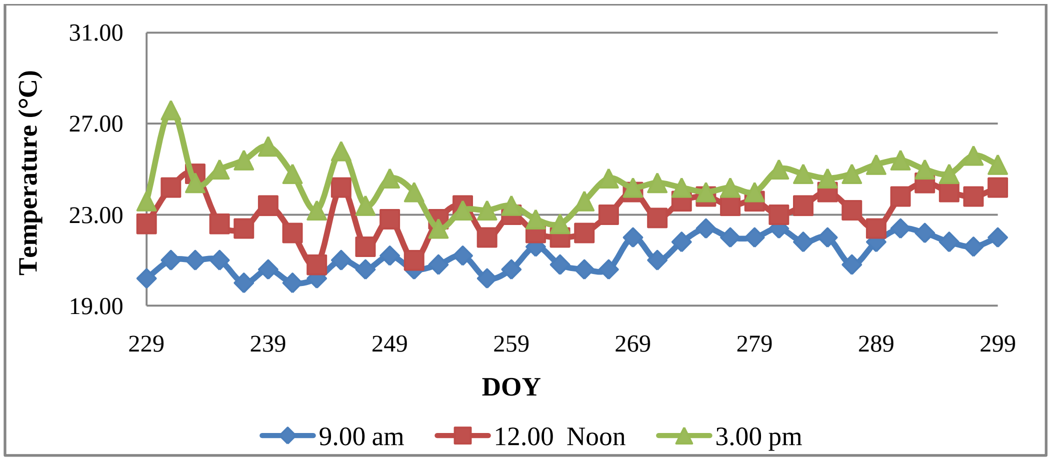

Figure 4.13: Variation of soil temperature within Kyondoni greenhouse

Figure 4.14 shows the variation of soil temperature within the greenhouse at Matinyani. The minimum and maximum values were 18.40 ^{o}C and 27.80 ^{o}C reached on DOY 221 and 198 respectively while the mean value for the duration of the study was 22.85 ^{o}C. Despite the fluctuations in soil temperature, the mean value was within the optimal soil temperature range for tomato crop (Popovski, 1997).

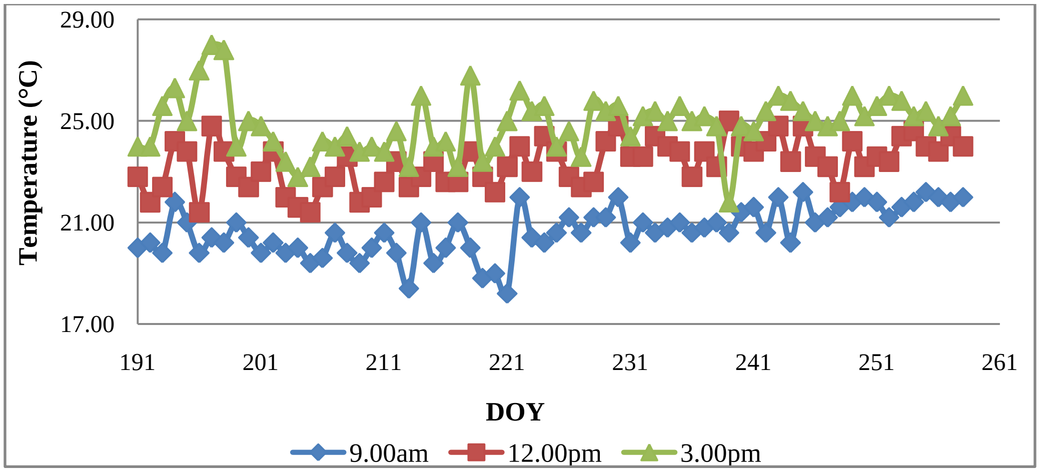

Figure 4.14: Variation of soil temperature within Matinyani greenhouse

4.2.8. Net Radiation Energy

The main driving variable of ETo calculated using the Priestley-Taylor model was net radiation (Grey, 2010). The calculation of net radiation energy was achieved prior to the estimation of daily clear day solar irradiance, net emissivity, net longwave radiation energy and D (constant) value (refer to appendices C and D).

Figure 4.15 shows the variation of estimated net radiation energy within the greenhouse at Kyondoni. The minimum and maximum net radiation energy values in the month of August were 19.87 and 20.99 MJ m^{-2} day^{-1} reached on DOY 237 and 243 respectively while the average value for the month was 20.40 MJ m^{-2} day^{-1}. In the month of September, the minimum and maximum values were 20.34 and 21.31 MJ m^{-2} day^{-1} reached on DOY 251 and 265 respectively while the average value for the month was 20.74 MJ m^{-2} day^{-1}. Similarly in the month of October, the minimum and maximum net radiation energy values were 20.02 and 21.43 MJ m^{-2}

day^{-1} recorded on DOY 275 and 279 respectively while the mean value for the month was 21.03 MJ m^{-2} day^{-1}. Similarly, the average net radiation energy value for the duration of the study was 20.77 MJ m^{-2} day^{-1}.

The results indicated that the month of August had the minimum value of net radiation energy and this was probably due to the fact that it was a cooler month. Figure 4.15 shows that net radiation energy fluctuated more between DOY 229 and 279 but stabilized from DOY 279 up to the end of the experiment (DOY 299). This was attributed to the unstable temperatures experienced between DOY 229 and 279.

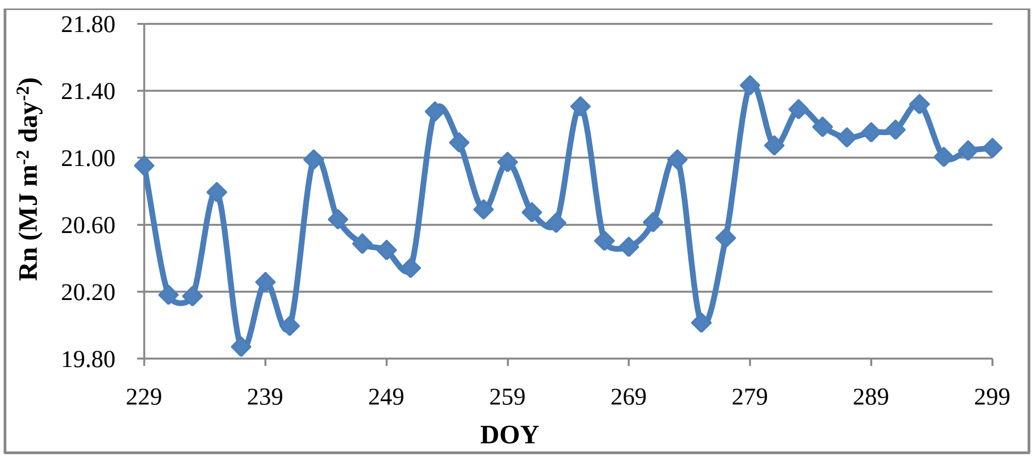

Figure 4.15: Variation of net radiation energy within Kyondoni greenhouse

Figure 4.16 shows the variation of net radiation energy within the greenhouse at Matinyani. The months of July and September recorded the highest values of net radiation energy while August recorded the least. In the month of July, the minimum and maximum net radiation energy values were 20.21 and 22.29 MJ m^{-2}

day^{-1} reached on DOY 208 and 199 respectively while the average value for the month was 21.92 MJ m^{-2} day^{-1}. Likewise, in the month of August, the minimum and maximum net radiation energy values were 20.36 and 21.80 MJ m^{-2} day^{-1} reached on DOY 237 and 217 respectively while the mean value for the month was 21.18 MJ m^{-2} day^{-1}. Lastly, in the month of September, the minimum and maximum radiation energy values were 20.76 and 21.86 MJ m^{-2} day^{-1} reached on DOY 250 and 251 while the average value for the month was 21.27 MJ m^{-2} day^{-1}. Figure 4.16 indicated that net radiation energy fluctuated at a high rate throughout the experiment and this was also attributed the changing climatic conditions experienced in the area.

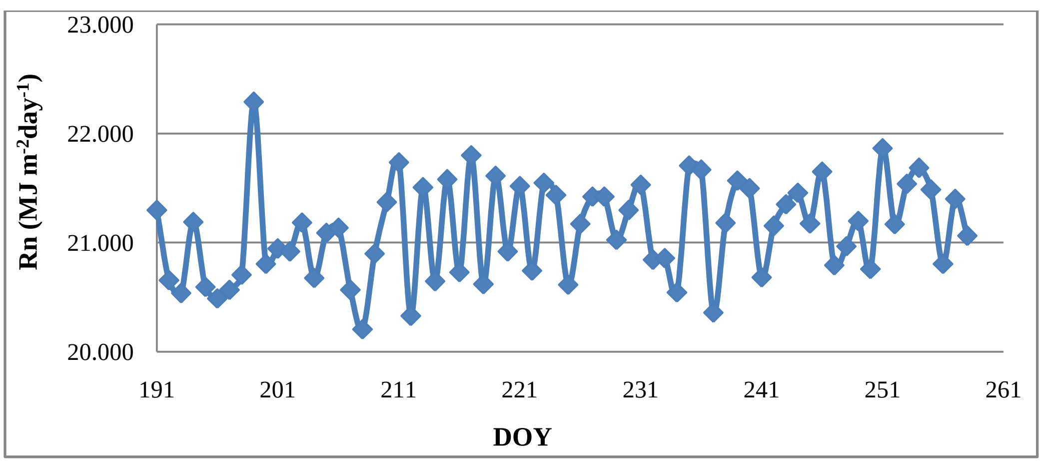

Figure 4.16: Variation of net radiation energy within Matinyani greenhouse

4.3. Water Requirements

4.3.1. Reference Evapotranspiration and Crop Water Requirements

Figure 4.17 shows the variation of reference evapotranspiration, ETo within the greenhouse at Kyondoni. According to the figure, ETo fluctuated throughout the duration of the study reaching a minimum of 6.84 mm day^{-1} on DOY 231 and a maximum of 7.78 mm day^{-1} on DOY 293. The average ETo values of the month in August, September and October were 7.03, 7.29 and 7.53 mm day^{-1} respectively while the average value for the duration of the study was 7.28 mm day^{-1}. The high values of ETo in the month of October were attributed to the high temperatures recorded within the greenhouse which could have probably increased evapotranspiration.

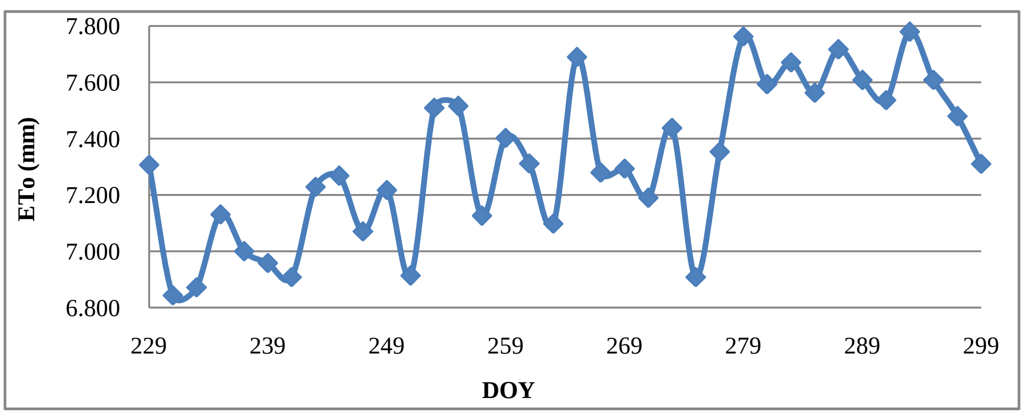

Figure 4.17: Variation of reference evapotranspiration within Kyondoni greenhouse

Figure 4.18 shows the variation of ETo within the greenhouse at Matinyani. The minimum and maximum values of ETo were 7.09 and 8.17 mm day^{-1} reached on

DOY 218 and 251 respectively while the average value for the duration of the study was 7.61 mm day^{-1}. The average ETo values of the month in July, August and September were 7.51, 7.55 and 7.86 mm day^{-1} respectively. Figure 4.18 shows that the fluctuation of ETo remained quite high throughout the duration of the study and this could have been due to the changing climatic conditions experienced in the area.

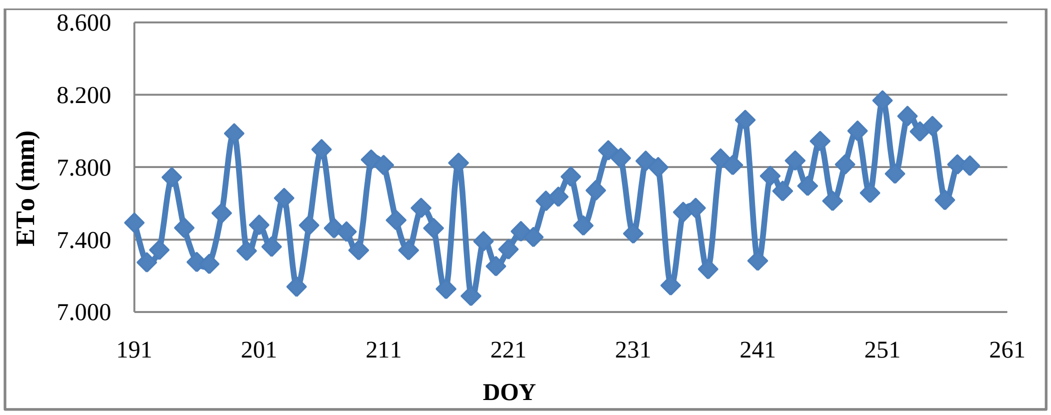

Figure 4.18: Variation of reference evapotranspiration within Matinyani greenhouse

The average crop water requirement per plant per day was 1.37 and 1.28 litres per plant per day at Matinyani and Kyondoni greenhouses respectively. These results indicated that the crop water requirement at Matinyani was higher compared to Kyondoni. This variation in crop water requirement was attributed to the high temperatures recorded in Matinyani for the duration of the study period which could have increased evapotranspiration rate within the greenhouse. According to Hendricks (2012), a mature tomato crop grown in open field requires 2-3 litres of water per plant per day during the summer months when light levels are high. In comparison, the results indicate that greenhouse farming reduces crop water requirements hence it can be used as an alternative to open field farming (Harmanto *et al*., 2005).

4.3.2. Applied Irrigation Water and Actual Crop Evapotranspiration

Table 4.7 summarizes the irrigation water requirement per plant per treatment and the variables of soil water balance at the experimental sites estimated for the duration of study. Irrigation water requirements per plant varied from 2.229 to 1.114 litres and from 1.975 to 0.988 litres in treatments T_1 to T_4 at Matinyani and Kyondoni greenhouses respectively. Consequently, the total applied irrigation water varied from 547.94 to 273.97 mm at Matinyani and from 255.13 to 127.56 mm at Kyondoni in all treatments. Likewise, the actual crop evapotranspiration varied from 536.96 to 245.80 mm at Matinyani and from 227.02 to 108.09 mm at Kyondoni in all treatments.

Table 4.6: A summary of water balance within the greenhouses

Location	Treatment	IWR ($Lp^{-1}d^{-1}$)	I (mm)	ΔS (mm)	ETc (mm)
Matinyani	T_1	2.229	547.94	-10.98	536.96
	T_2	1.859	456.62	-14.07	442.55
	T_3	1.486	365.29	-17.01	348.28
	T_4	1.114	273.97	-28.17	245.80
Kyondoni	T_1	1.975	255.13	-28.11	227.02
	T_2	1.646	212.61	-18.44	194.17
	T_3	1.317	170.09	-17.86	152.23
	T_4	0.988	127.56	-19.47	108.09

Key: IWR = Irrigation water requirement; I = Total irrigation water applied; ΔS = Change in soil water content; ETc = Actual evapotranspiration.

Changes in soil water content in treatments under daily irrigation frequency increased with decrease in applied irrigation water. This implied that higher water application levels could have maintained the available water to nearly optimum levels hence the change in soil water storage remained low (Sezen *et al*. 2006). However, treatment T_4 had the highest soil water content and this was an indication that the available water was limited and this could have caused higher the soil water depletion.

With respect to the treatments irrigated at alternate days, it was noted that soil water content decreased with decrease in applied irrigation water. This was an indication that available water was limited in the soil and plants utilized the replenished water to sustain their growth, (Sezen *et al*., 2006).

4.4. Observations about Crop Growth

4.4.1. Plant Height

Etissa *et al*. (2014) found out that the plant height of tomato crop responded linearly to applied irrigation water. Similarly, Demirtas and Ayas (2009) found out that the height of pepper crop responded linearly with applied irrigation water. In this study, the relationship between the height of tomato crop and applied irrigation water was found to be linear. Figure 4.19 shows the relationship between plant height and applied irrigation water at Kyondoni greenhouse. In this respect, treatment T_4 produced the best correlation (R^2 = 0.989) while treatment T_2

produced the least (R^2 = 0.979). On the same note, treatment T_3 had a better correlation (R^2 = 0.986) than T_1 (R^2 = 0.979).

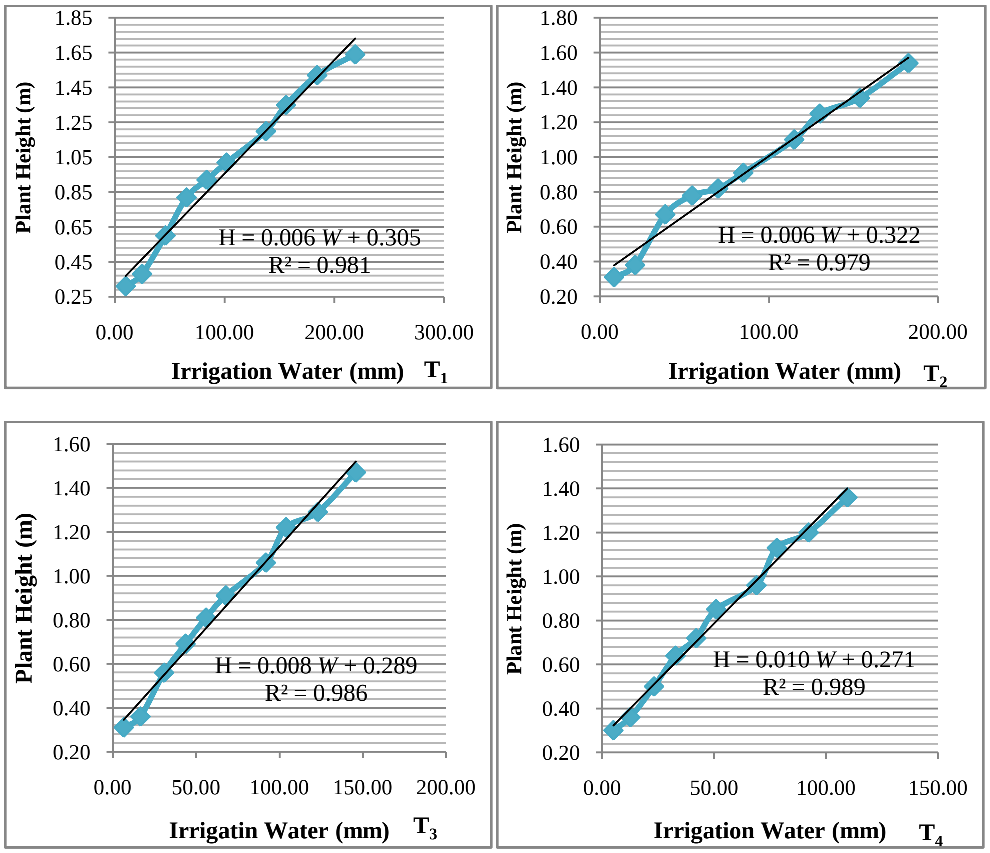

Figure 4.19: Variation of plant heights with irrigation water within Kyondoni greenhouse

Positive linear relationships were also found between plant height and applied irrigation water at Matinyani. Figure 4.20 shows that the best correlation was found in treatment T_3 (R^2 = 0.990) while the least (R^2 = 0.953) was found in treatment T_1. These correlation values indicated that the applied irrigation water in treatment T_3 was optimum for plant growth whereas that applied in treatments T_1 and T_2 was probably too excessive and therefore it could have depleted the root zone of much needed oxygen hence reducing both root growth and nutrient uptake. The correlation value found in treatment T_4 was higher than the values found in treatments T_1 and T_2. This was an indication that the amount of irrigation water applied to this treatment was slightly adequate to support plant growth. These results are in agreement with those by Demirtas and Ayas (2009) that deficit irrigation has an effect on the plant height of the crop.

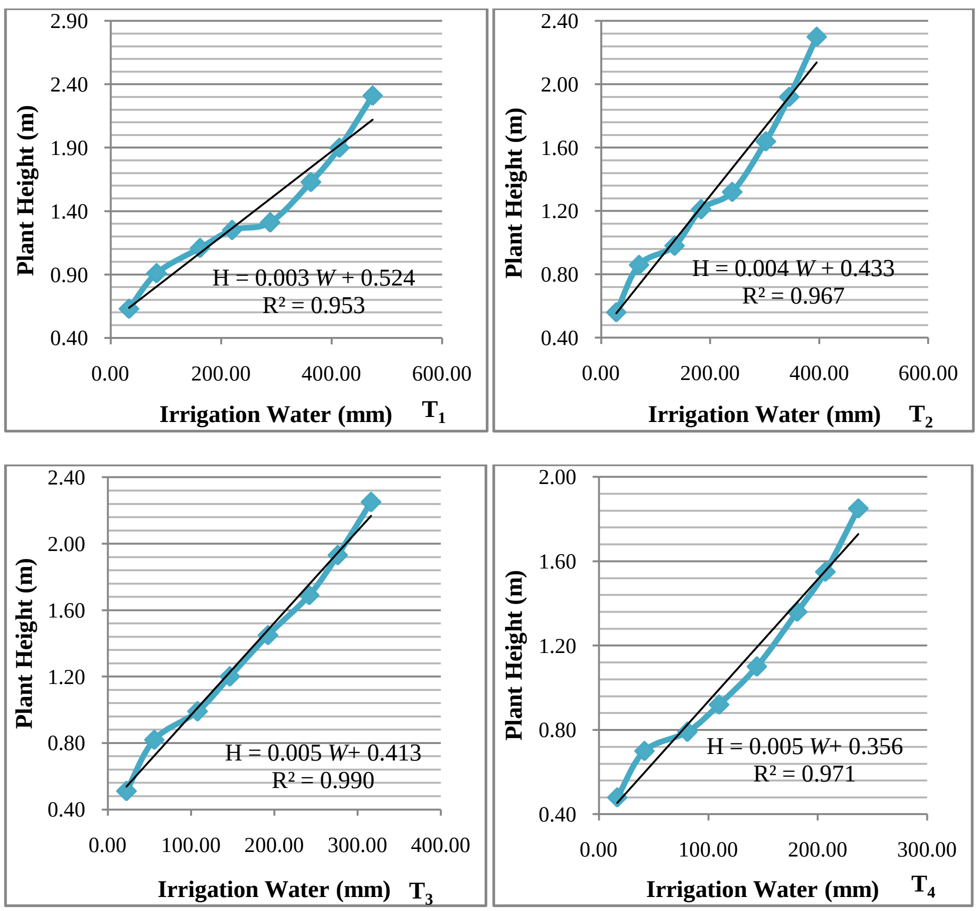

Figure 4.20: Variation of plant height with irrigation water within Matinyani greenhouse

In general, the results indicated that the plant heights decreased as the amount of irrigation water applied and irrigation frequency were decreased (Etissa *et al.*, 2014; Harmanto *et al*., 2005). However, the study found out that the height of tomato crop responds linearly to the applied irrigation water irrespective of the amount and frequency.

4.4.2. Stem Diameter

In this study, the relationship between stem diameter of tomato crop and applied irrigation water was a logarithmic function. This was in agreement with the analysis done by Etissa *et al*. (2014). Figure 4.21 shows the variation of stem diameter with irrigation water within the greenhouse at Kyondoni. The best correlation was found in treatment T_1 (R^2 = 0.779) while the least was found in treatment T_4 (R^2 = 0.717). Figure 4.22 shows the variation of stem diameter with applied irrigation water within Matinyani greenhouse where the best correlation (R^2 = 0.961) was found in treatment T_1 while the least (R^2 = 0.915) was in treatment T_4. The results implied that the stem diameter increased with increase in the applied irrigation quantity. Further, stem diameter decreased with decrease in irrigation frequency.

The study found out that the best correlation values between stem diameter and applied irrigation water were in treatments irrigated daily. This implied that low irrigation amount and less irrigation frequency reduced shoot development and consequently vegetative development (Hendricks, 2012). The reason could have been that the effect of water stress conditions became more effective as the crop matured (Owusu-Sekyere *et al*., 2009).

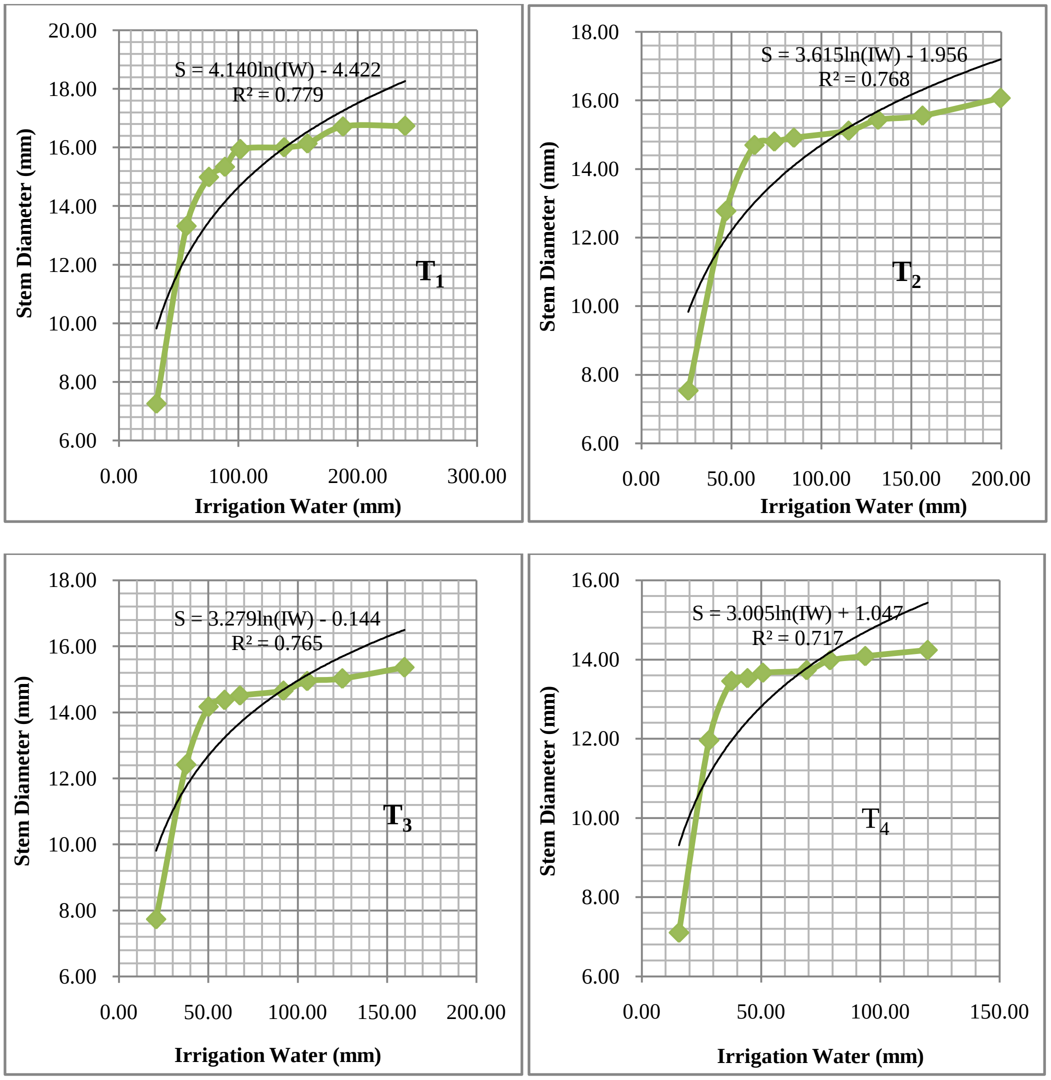

Figure 4.21: Variation of stem diameter with irrigation water within Kyondoni greenhouse

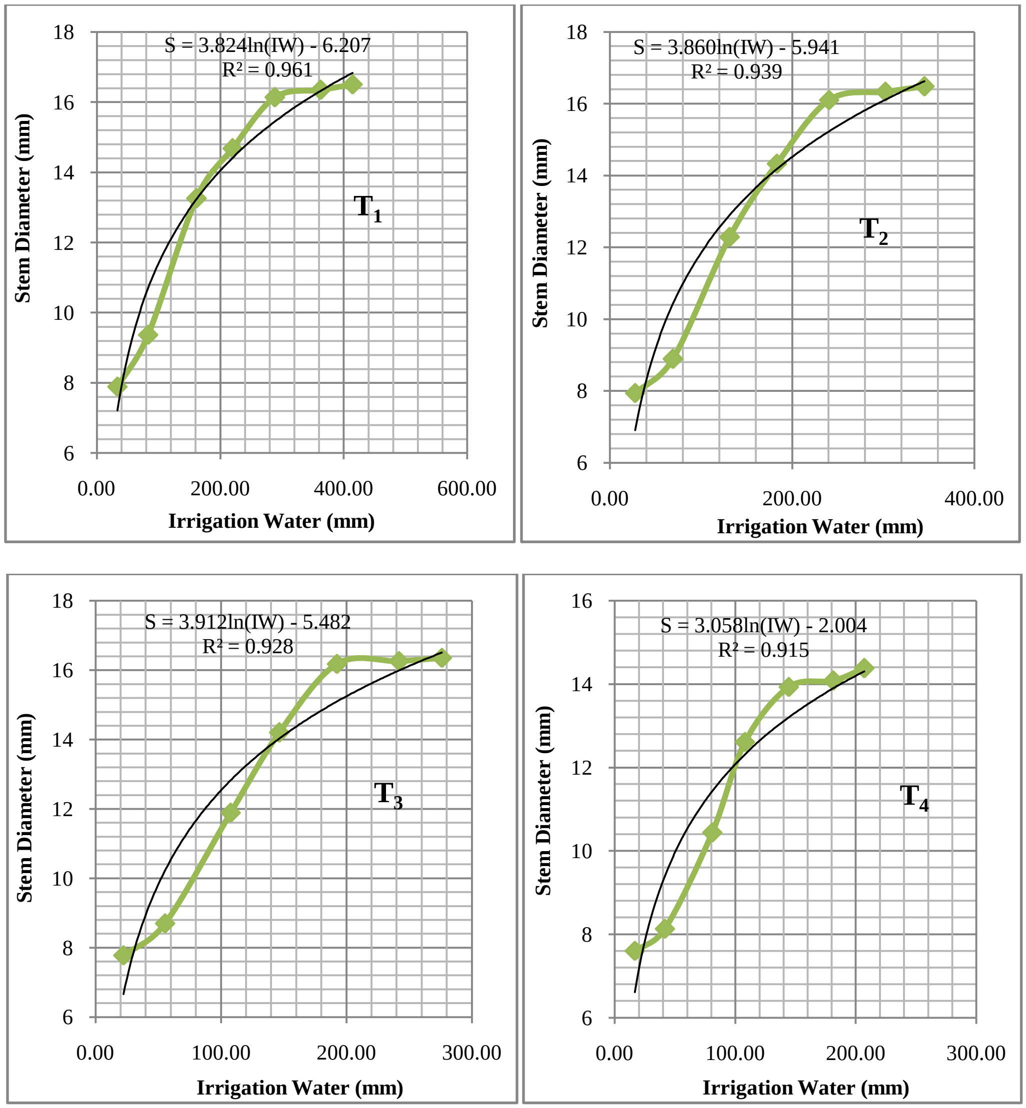

Figure 4.22: Variation of Stem Diameter with Irrigation Water within Matinyani greenhouse

4.4.3. Fruit Diameter

Figure 4.23 presents the average fruit diameter values for the treatments in both greenhouses. Generally, treatments T_1 and T_4 produced the largest and the smallest fruit diameter values in both greenhouses. At Kyondoni, the average fruit diameter varied from 59 to 45 mm in all treatments. Similarly, at Matinyani, the average fruit diameter varied from 62 and 53 mm in all treatments. The results indicated that smaller fruit diameters were obtained from treatments irrigated at alternate days and this was an indication that water stress reduced the fruit diameter. Both irrigation quantity and irrigation frequency affected the fruit diameter and this confirms the inference drawn by Owusu-Sekyere *et al*. (2009).

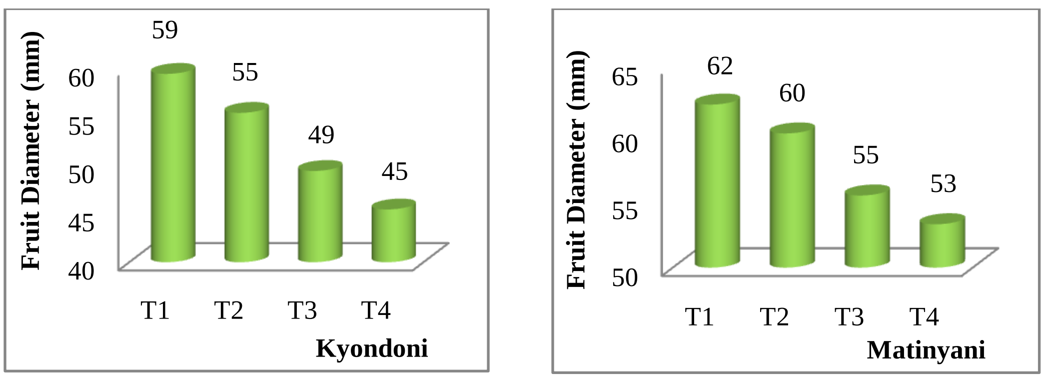

Fig 4.23: Variation of fruit diameter between treatments

Harmanto *et al*. (2005) used fruit diameter and fruit weight to quantify fruit quality. Using the same criterion, the best fruit quality was obtained from daily irrigated treatments. This was probably due to the fact that fruit diameter was highly influenced by applied irrigation water and as such the treatment which received the least had the least fruit diameter.

4.4.4. Fruit Weight

Figure 4.24 presents the average fruit weights measured in both greenhouses where treatments T_1 produced the highest fruit weight while treatments T_4 produced the least. The weights varied from 129 to 111 g and from 124 to 98 g in all treatments at Matinyani and Kyondoni respectively.

Figure 4.24 shows that the highest fruit weight was obtained from daily irrigated treatments and the least from treatments irrigated at alternate days. This was attributed to the fact that the availability of the right amount of water in the soil enhances the development and final yield of the fruit (Sezen *et al*., 2006). Deficit irrigation imposes stress thus making the plants unable to efficiently make use of available nutrients for growth and yield development (Owusu Sekyere *et al*., 2009). Fruit weight is closely associated with lack of soil water in the root zone therefore when soil water deficit in the root zone increases there is loss in turgidity and a reduction in growth and fruit weight.

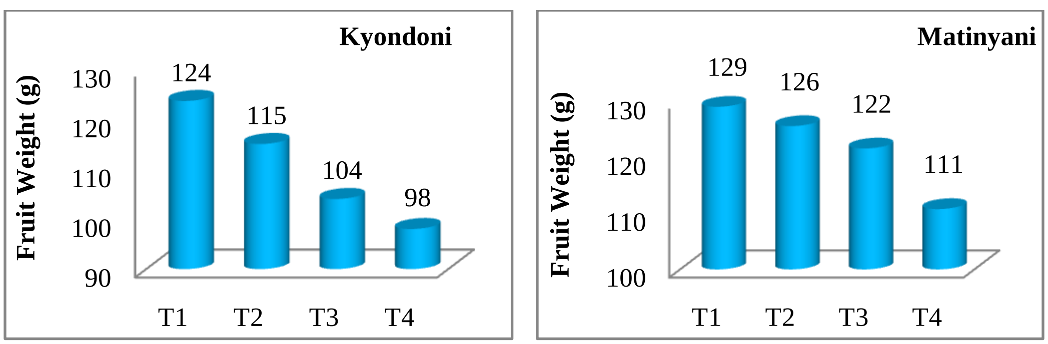

Figure 4.24: Variation of fruit weights between treatments

4.4.5. Tomato Yield

In both greenhouses, the highest yield was obtained in treatments T_1 while the lowest yield was obtained in treatments T_4. Figure 4.25 shows that the yield varied from 4.44 to 3.26 kg m^{-2} at Matinyani and from 2.74 to 1.04 kg m^{-2} at Kyondoni in all treatments. The highest yield was obtained from daily irrigated treatments but application of irrigation at lower quantity (deficit irrigation) of the water requirement resulted in lower yield, (Harmanto *et al*., 2005). This probably was due to the fact that the available amount water in soil plays an active role in the root activity and since different water amounts were applied to the treatments, soil water amounts consumed by tomatoes differed. The study found out that yield was influenced by the quantity of irrigation and irrigation frequency (Etissa *et al*., 2014; Sezen *et al*., 2006). Therefore, for high yields, an adequate water supply and relatively moist soils are required during the total growth period (Bozkurt and Mansuroglu, 2011).

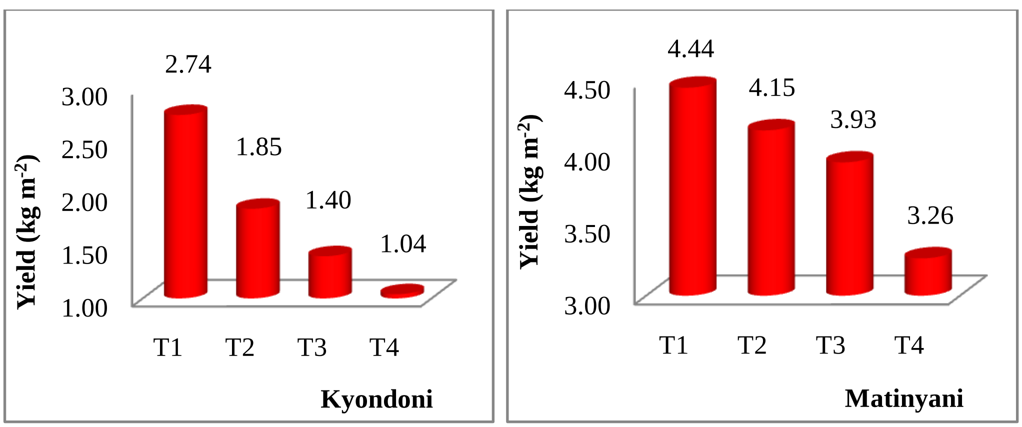

Figure 4.25: Variation of tomato yield between treatments

4.5. Irrigation Water Productivity (IWP)

Table 4.12 summarizes data on yield, water use efficiency (WUE) and irrigation water use efficiency (IWUE) for both greenhouses. For alternate and daily irrigation frequencies, treatments T_1 and T_4 produced the best IWUE and WUE as 10.74 and 12.07 kg m^{-3} and 11.90 and 13.26 kg m^{-3} respectively.

When irrigation was done daily, it was observed that IWUE and WUE values increased with decrease in applied irrigation water. In this regard, among the drip irrigation levels tested, the best IWP was found in the lowest level of irrigation at 60% ETc (T_4), indicating comparatively the more efficient use of irrigation water. This was an indication that higher irrigation quantity resulted in lower IWUE and WUE values which is in agreement with the earlier findings of Dunage *et al*. (2009) and Harmanto *et al*. (2005). However, this was not the case with alternate irrigation because IWUE values decreased with decrease in applied irrigation water. Similarly, WUE values decreased with decrease in quantity of irrigation water except in treatment T_4. This was an indication that lower irrigation quantity led to extreme soil water stress and this led to the low yield obtained from these treatments.

Table 4.7: Summary of Yield, Water use Efficiencies and Irrigation Water use Efficiencies

Matinyani greenhouse				**Kyondoni greenhouse**			
Irrigation treatment	Yield (kg m^{-2})	IWUE (kg m^{-3})	WUE (kg m^{-3})	Irrigation treatment	Yield (kg m^{-2})	IWUE (kg m^{-3})	WUE (kg m^{-3})
T_1	4.44	8.10	8.27	T_1	2.74	10.74	12.07
T_2	4.15	9.09	9.38	T_2	1.85	8.70	9.53
T_3	3.96	10.84	11.37	T_3	1.40	8.23	9.50
T_4	3.26	11.90	13.26	T_4	1.04	8.15	9.62

4.6. Soil Water Content

Water management of tomato crop is extremely important at all stages of plant development due to its influence on stand establishment, fungal problems, fruit set and quality (Jaria 2012). Figure 4.26 shows the variation of volumetric water content with days after transplanting within the greenhouses. In both greenhouses, soil water content remained fairly high in treatments T_1 because they received more irrigation water. According to fig. 4.26, at about 30 days after transplanting, treatments in both greenhouses showed high levels of soil water content in the 0 – 30 cm soil profile but later considerable differences were noted. Soil water remained higher in treatments T_1 and T_2 than the other treatments considered. As the amount of applied irrigation water decreased, soil water storage also decreased. Water stress gradually increased in the alternate irrigated treatments and reduced fruit yield significantly (Sezen *et al*., 2006).

Figure 4.26 shows that the depletion of soil water over time reflected an undulating profile with a number of peaks and troughs dispersed throughout the treatments. This was attributed to the variation of crop water use at various stages of growth.

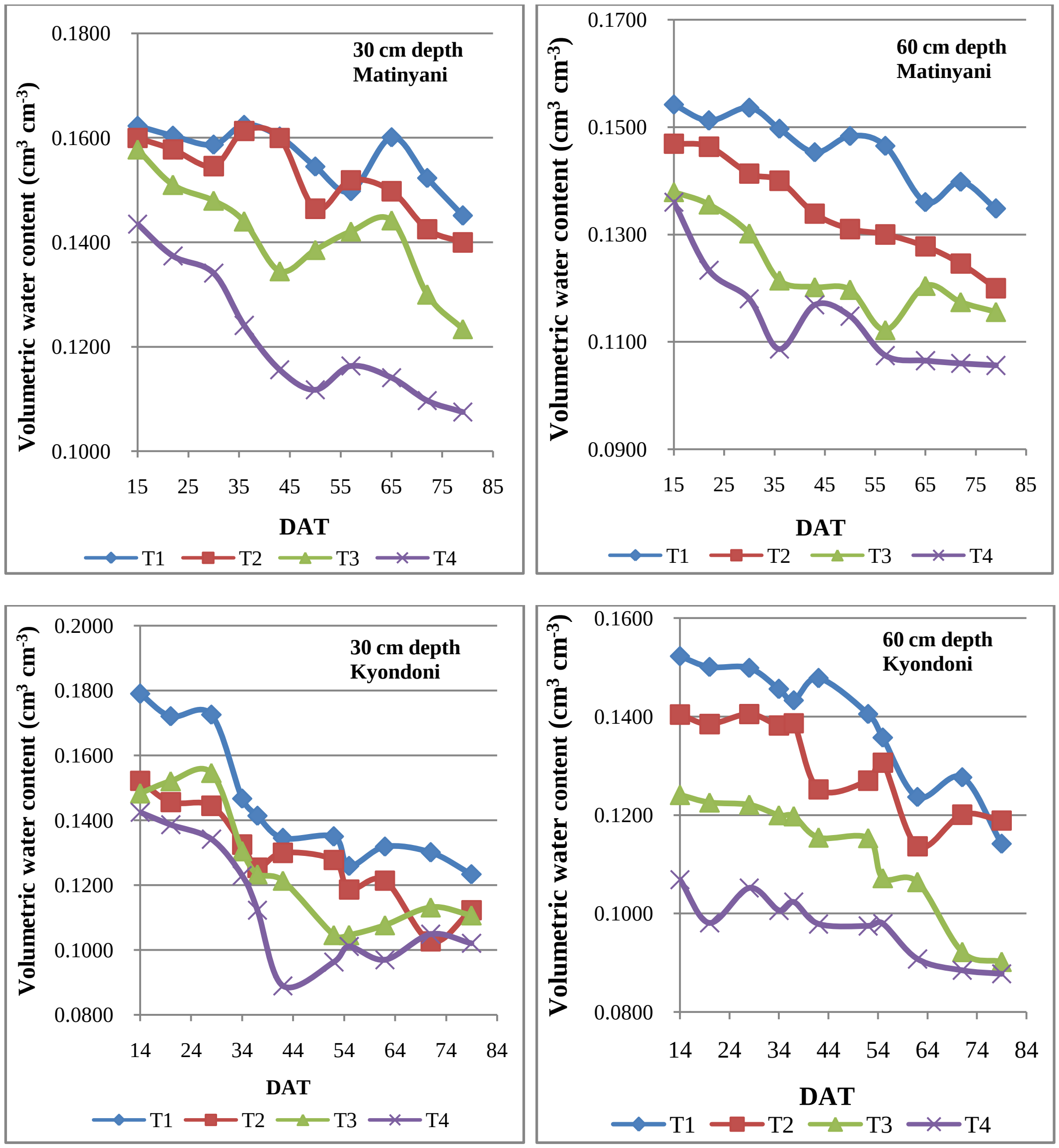

Figure 4.26: Variation of volumetric soil water content with days after transplanting within the greenhouses

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

1. The estimation of the reference evapotranspiration (ETo) taking into account the microclimate parameters mainly temperature can constitute an approach to estimate crop water requirements.
2. A significant reduction in growth parameters (plant height, plant diameter and stem diameter), yield and soil water content was observed based on reductions in irrigation water applications and frequency. Thus, tomato crop should be irrigated daily at full water irrigation in order to obtain maximum yield.
3. Soil bulk density indicated a gradual increase with depth down the profile. Basically, soil bulk density is an indicator of soil compaction and soil health and it influences key soil processes and productivity hence it could have slightly affected the crop growth parameters, yield and soil water balance.
4. When irrigation was done daily, IWUE and WUE increased with decrease in applied irrigation water with the highest recorded in treatment T_4 (60 % ETc). However, this was not the order when irrigation was done alternate.

5.2. Recommendations

1. Daily irrigation frequency is the most preferable in greenhouses located in semi-arid environments because it ensures availability of water in soil which plays an active role in the root activity of the crop.
2. Deficit irrigation applied in greenhouse farming during any reproductive growth stage in tomato would not be beneficial if the aim is to maximize yield. However, if the aim is to maximize greenhouse production under limited water supply, deficit irrigation may be feasible during the vegetative phase for tomato.
3. To ensure favorable regulation of plant environment in a greenhouse, the microclimate parameters need to be identified. If greenhouse farming is practiced it is important to monitor the microclimate variables because this will help them to manage crop production and to improve the ventilation of the greenhouse.
4. A 20 % reduction in the quantity of irrigation water could be considered in tomato production under greenhouse conditions if water economics is to be practiced to improve net profit of production. However, full irrigation treatment could be used in areas with no water shortage conditions.

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APPENDICES

Appendix A: Definitions

Crop evapotranspiration (ETc)

Crop evapotranspiration is the amount of water used by a crop at any growth stage, since the sowing / planting date up until the harvest, whenever there is no water restriction in the soil, (Allen *et al*., 1998). This process is also called crop maximum evapotranspiration, (Baille, 1996).

Evapotranspiration (ET)

Evapotranspiration is the simultaneous process of water transfer to the atmosphere both by soil water evaporation and plants transpiration, (Allen *et al*., 1998).

Greenhouse

A Greenhouse is a frame of inflated structure covered with a transparent material in which crops are grown under controlled environment conditions, (Popovski, 1997).

Greenhouse climate

Popovski (1997) defines greenhouse climate as a composition of parameters that are variable and interdependent and which are mainly influenced by the external climate changes and the stage of the plant development.

Greenhouse Cultivation

Greenhouse cultivation also known as protected cultivation is a system of farming which provides and maintains a controlled environment suitable for optimum crop production by creating a sheltered environment for plants by using solar radiation to trap heat, (Demirtas and Ayas, 2009).

Potential evapotranspiration

Potential evapotranspiration is the maximal evaporation rate that the atmosphere is capable of extracting from a well-watered field under given condition, (Baille, 1996).

Water Balance

The water balance is an account of all quantities of water added to, subtracted from and stored within the root zone during a given period of time, (Simba, 2010).

Appendix B: Map of Kitui County

Appendix C: Microclimate variables measured and estimated within Matinyani greenhouse

DOY	T	Tm	Td	Δ	e°	e^a	e° - e^a	RH	D	Rso	ε′	Rln	Rn	ETo	P	CWR
191	25.73	21.65	21.00	0.1960	3.3088	2.4870	0.8218	75.16	0.0832	33.4483	0.1208	4.458	21.297	7.493	0.70	0.944
192	25.80	19.95	20.50	0.1967	3.3219	2.0406	1.2813	61.43	0.0837	33.4482	0.1414	5.099	20.656	7.274	0.70	0.916
193	27.13	21.65	20.50	0.2106	3.5926	2.0406	1.5520	56.80	0.0841	33.4482	0.1414	5.218	20.537	7.343	0.70	0.925
194	27.73	23.40	21.00	0.2338	4.0077	2.4870	1.5207	62.06	0.0845	33.4482	0.1208	4.565	21.190	7.744	0.70	0.976
195	28.40	20.85	20.50	0.2246	3.8689	2.0406	1.8283	52.74	0.0850	33.4482	0.1414	5.162	20.593	7.464	0.70	0.941
196	26.53	20.95	20.00	0.2042	3.4682	1.9855	1.4827	57.25	0.0854	33.4482	0.1441	5.267	20.488	7.276	0.75	0.982
197	30.67	24.15	21.50	0.1994	3.4947	2.1550	1.3397	61.66	0.0858	33.4482	0.1359	5.188	20.568	7.266	0.75	0.981
198	28.93	22.15	21.50	0.2307	3.9895	2.1550	1.8345	54.02	0.0863	33.4481	0.1359	5.049	20.706	7.546	0.75	1.019
199	27.33	22.70	25.00	0.2127	3.6350	3.1678	0.4672	87.15	0.0867	33.4481	0.0926	3.466	22.289	7.987	0.75	1.078
200	25.93	22.05	22.00	0.1980	3.3476	2.2095	1.1381	66.00	0.0872	33.4481	0.1334	4.950	20.805	7.337	0.75	0.991
201	27.03	21.45	19.50	0.2095	3.5716	2.2669	1.3047	63.47	0.0876	33.4481	0.1307	4.810	20.945	7.480	0.80	1.077
202	25.73	20.35	22.00	0.1960	3.3082	2.2095	1.0987	66.79	0.0880	33.4481	0.1334	4.837	20.918	7.360	0.80	1.625
203	27.80	23.50	21.00	0.2179	3.7361	2.4870	1.2491	66.57	0.0885	33.4480	0.1208	4.571	21.184	7.630	0.80	1.685
204	24.20	19.65	20.50	0.1810	3.0199	2.0406	0.9793	67.57	0.0889	33.4480	0.1414	5.078	20.677	7.139	0.80	1.576
205	26.40	25.00	21.00	0.2028	3.4418	2.4870	0.9548	72.26	0.0893	33.4480	0.1208	4.664	21.091	7.479	0.80	1.651
206	31.53	26.40	21.50	0.2625	4.6299	2.5644	2.0655	55.39	0.0898	33.4480	0.1174	4.619	21.136	7.897	0.80	1.744
207	28.50	25.55	22.00	0.2257	3.8914	2.2095	1.6819	56.78	0.0902	33.4480	0.1334	5.189	20.566	7.462	0.80	1.648
208	30.00	26.20	20.50	0.2434	4.2431	2.0406	2.2025	48.09	0.0906	33.4480	0.1414	5.548	20.207	7.443	0.80	1.643
209	25.60	20.65	22.00	0.1946	3.2828	2.2095	1.0733	67.31	0.0911	33.4479	0.1334	4.856	20.898	7.341	0.80	1.621

210	29.60	22.50	21.50	0.2385	4.1467	2.5644	1.5823	61.84	0.0915	33.4479	0.1174	4.383	21.372	7.842	0.80	1.731
211	27.60	20.60	22.50	0.2157	3.6928	2.7257	0.9671	73.81	0.0933	33.4479	0.1105	4.020	21.735	7.811	0.80	1.725
212	30.27	24.55	20.00	0.2467	4.3092	2.0406	2.0504	47.35	0.0924	33.4479	0.1414	5.427	20.328	7.507	0.80	1.658
213	23.33	18.15	21.00	0.1729	2.8660	2.4870	0.3790	86.78	0.0928	33.4479	0.1208	4.250	21.505	7.341	0.80	1.621
214	29.60	24.40	22.00	0.2385	4.1467	2.2095	1.9372	53.28	0.0933	33.4478	0.1334	5.109	20.646	7.575	0.80	1.673
215	24.33	18.95	21.50	0.1822	3.0435	2.5644	0.4791	84.26	0.0937	33.4478	0.1174	4.176	21.579	7.463	0.80	1.648
216	23.87	18.90	20.50	0.1779	2.9607	2.0406	0.9201	68.92	0.0941	33.4478	0.1414	5.026	20.729	7.126	0.80	1.574
217	27.47	19.40	22.50	0.2142	3.6648	2.7256	0.9392	74.37	0.0946	33.4478	0.1105	3.955	21.800	7.824	0.80	1.727
218	23.87	19.10	20.00	0.1779	2.9607	1.9855	0.9752	67.06	0.0950	33.4478	0.1441	5.136	20.619	7.089	0.80	1.565
219	23.87	18.35	21.50	0.1741	2.8978	2.5644	0.3334	88.49	0.0954	33.4478	0.1174	4.142	21.613	7.391	0.80	1.632
220	24.53	20.35	22.00	0.1841	3.0802	2.2095	0.8707	71.73	0.0959	33.4477	0.1334	4.837	20.918	7.252	0.80	1.601
221	23.33	20.00	21.50	0.1729	2.8660	2.5644	0.3016	89.48	0.0963	33.4477	0.1174	4.236	21.518	7.346	0.80	1.622
222	27.47	22.95	22.00	0.2142	3.6648	2.2095	1.4553	60.29	0.0967	33.4477	0.1334	5.010	20.744	7.445	0.85	1.747
223	23.93	19.50	21.50	0.1784	2.9714	2.5644	0.4070	86.30	0.0972	33.4477	0.1174	4.207	21.547	7.414	0.85	1.739
224	26.53	21.40	21.50	0.2042	3.4682	2.5644	0.9038	73.94	0.0976	33.4477	0.1174	4.318	21.437	7.613	0.85	1.786
225	30.60	24.85	22.00	0.2507	4.3913	2.2095	2.1818	50.32	0.0980	33.4476	0.1334	5.140	20.614	7.637	0.85	1.792
226	29.33	25.80	21.50	0.2353	4.0827	2.5644	1.5183	62.81	0.0985	33.4476	0.1174	4.582	21.173	7.748	0.85	1.818
227	25.07	19.55	21.00	0.1894	3.1810	2.4870	0.6940	78.18	0.0989	33.4476	0.1208	4.332	21.422	7.477	0.85	1.754
228	27.27	21.65	21.50	0.2121	3.6222	2.5644	1.0578	70.80	0.0993	33.4476	0.1174	4.332	21.422	7.671	0.85	1.800
229	32.07	26.05	21.00	0.2696	4.7736	2.4870	2.2866	52.10	0.0998	33.4476	0.1208	4.730	21.024	7.893	0.85	1.852
230	30.07	23.75	21.50	0.2442	4.2601	2.5644	1.6957	60.20	0.1002	33.4476	0.1174	4.457	21.297	7.850	0.85	1.842
231	24.20	19.80	21.50	0.1810	3.0200	2.5644	0.4556	84.91	0.1007	33.4475	0.1174	4.225	21.530	7.433	0.85	1.744
232	32.20	24.90	20.00	0.2713	4.8088	2.3383	2.4705	48.63	0.1011	33.4475	0.1274	4.912	20.842	7.834	0.85	1.838

233	31.60	24.65	20.00	0.2634	4.6483	2.3383	2.3100	50.30	0.1015	33.4475	0.1274	4.896	20.859	7.798	0.85	1.193
234	24.80	20.50	17.50	0.1867	3.1302	2.0000	1.1302	63.89	0.1020	33.4475	0.1434	5.210	20.545	7.147	0.85	1.094
235	24.80	19.55	19.50	0.1867	3.1302	2.6690	0.4612	85.27	0.1024	33.4475	0.1129	4.049	21.706	7.551	0.85	1.155
236	25.20	20.25	19.50	0.1906	3.2057	2.6690	0.5367	83.26	0.1028	33.4474	0.1129	4.088	21.667	7.575	0.85	1.159
237	26.60	21.50	17.00	0.2049	3.4825	1.9377	1.5448	55.64	0.1033	33.4474	0.1465	5.395	20.359	7.236	0.85	1.107
238	30.60	25.05	21.00	0.2507	4.3913	2.5425	1.8488	57.90	0.1037	33.4474	0.1184	4.575	21.180	7.846	0.85	1.200
239	28.33	22.00	19.50	0.2238	3.8532	2.6690	1.1842	69.27	0.1041	33.4474	0.1129	4.186	21.568	7.812	0.85	1.195
240	31.93	24.85	22.50	0.2678	4.7360	2.7256	2.0104	57.55	0.1046	33.4474	0.1105	4.258	21.497	8.060	0.85	1.233
241	25.80	20.15	18.00	0.1967	3.3219	2.0640	1.2579	62.13	0.1050	33.4474	0.1403	5.073	20.682	7.282	0.85	1.114
242	29.47	22.00	20.50	0.2370	4.1158	2.4116	1.7042	58.59	0.1054	33.4473	0.1241	4.602	21.153	7.751	0.80	1.116
243	27.53	20.75	21.00	0.2149	3.6777	2.4870	1.1907	67.62	0.1059	33.4473	0.1208	4.404	21.351	7.667	0.80	1.104
244	29.13	21.05	21.50	0.2330	4.0359	2.5644	1.4715	63.54	0.1063	33.4473	0.1174	4.297	21.457	7.836	0.80	1.128
245	28.67	21.65	20.50	0.2277	3.9299	2.4116	1.5183	61.37	0.1068	33.4473	0.1241	4.580	21.175	7.697	0.80	1.108
246	29.60	24.50	23.00	0.2385	4.1467	2.8094	1.3373	67.75	0.1072	33.4473	0.1070	4.104	21.651	7.944	0.80	1.144
247	29.40	21.90	19.00	0.2362	4.0992	2.1974	1.9018	53.61	0.1076	33.4472	0.1340	4.962	20.792	7.614	0.80	1.096
248	31.27	23.00	20.00	0.2592	4.5621	2.3383	2.2238	51.25	0.1081	33.4472	0.1274	4.788	20.966	7.815	0.80	1.125
249	32.67	23.25	21.00	0.2776	4.9378	2.4870	2.4508	50.37	0.1085	33.4472	0.1208	4.556	21.199	8.000	0.80	1.152
250	30.17	22.75	22.00	0.2454	4.2846	2.2095	2.0751	51.57	0.1089	33.4472	0.1334	4.997	20.757	7.658	0.80	1.103
251	31.53	23.00	23.50	0.2625	4.6299	2.8955	1.7344	62.54	0.1094	33.4472	0.1035	3.890	21.864	8.169	0.80	1.176
252	29.53	21.75	20.50	0.2381	4.1359	2.4116	1.7243	58.31	0.1098	33.4472	0.1241	4.586	21.168	7.764	0.80	1.118
253	32.00	22.50	19.50	0.2687	4.7548	2.6690	2.0858	56.13	0.1102	33.4471	0.1129	4.215	21.540	8.082	0.80	1.164
254	30.13	21.50	22.50	0.2449	4.2748	2.7256	1.5492	63.76	0.1107	33.4471	0.1105	4.070	21.685	7.997	0.80	1.152
255	31.53	23.45	19.50	0.2625	4.6299	2.6690	1.9609	57.65	0.1111	33.4471	0.1129	4.269	21.485	8.028	0.80	1.156

256	29.40	22.05	22.00	0.2362	4.0992	2.2095	1.8897	53.90	0.1116	33.4471	0.1334	4.950	20.805	7.618	0.80	1.097
257	29.13	22.00	21.50	0.2330	4.0359	2.5644	1.4715	63.54	0.1120	33.4471	0.1174	4.353	21.401	7.815	0.80	1.125
258	30.67	23.45	20.50	0.2516	4.4089	2.4116	1.9973	54.70	0.1124	33.4471	0.1241	4.693	21.062	7.808	0.80	1.124

(10th July, 2013 = DOY 191 and 15th September, 2013 = DOY 258)

Appendix D: Microclimate variables measured and estimated within Kyondoni greenhouse

DOY	T	Tm	Td	Δ	e°	eª	e° - eª	RH	D	Rso	ε'	Rln	Rn	ETo	P	CWR
229	25.00	19.50	19.00	0.1887	3.1678	2.1974	0.9704	69.37	0.0993	33.4476	0.1340	4.802	20.952	7.307	0.70	0.921
231	22.83	19.50	15.50	0.1684	2.7807	1.7610	1.0197	63.33	0.1007	33.4475	0.1555	5.573	20.182	6.843	0.70	0.862
233	23.17	21.00	16.00	0.1715	2.8385	1.8183	1.0202	64.06	0.1015	33.4475	0.1526	5.582	20.173	6.872	0.70	0.866
235	23.67	18.50	18.00	0.1760	2.9253	2.0640	0.8613	70.56	0.1024	33.4475	0.1403	4.960	20.795	7.131	0.70	0.898
237	25.83	20.75	14.50	0.1970	3.3278	1.6512	1.6766	49.62	0.1033	33.4474	0.1614	5.884	19.871	7.000	0.75	0.945
239	23.80	18.50	15.50	0.1772	2.9483	1.7610	1.1873	59.73	0.1041	33.4474	0.1555	5.497	20.257	6.958	0.75	0.939
241	24.25	20.50	15.00	0.1815	3.0290	1.7053	1.3237	56.30	0.1050	33.4474	0.1585	5.758	19.996	6.909	0.75	0.933
243	24.00	20.75	19.50	0.1791	2.9839	2.2669	0.7170	75.97	0.1059	33.4473	0.1307	4.765	20.990	7.229	0.75	0.976
245	25.83	19.25	17.50	0.1970	3.3278	2.0000	1.3278	60.10	0.1068	33.4473	0.1434	5.122	20.633	7.268	0.75	0.981
247	24.17	19.75	17.00	0.1807	3.0145	1.9377	1.0768	64.28	0.1076	33.4472	0.1465	5.268	20.486	7.071	0.75	0.955
249	26.00	18.75	16.50	0.1987	3.3614	1.8772	1.4842	55.85	0.1085	33.4472	0.1496	5.307	20.448	7.217	0.75	0.974
251	23.00	18.75	16.00	0.1699	2.8094	1.8183	0.9911	64.72	0.1094	33.4472	0.1526	5.413	20.341	6.913	0.80	1.526
253	26.00	20.00	20.50	0.1987	3.3614	2.4116	0.9498	71.74	0.1102	33.4471	0.1241	4.478	21.276	7.510	0.80	1.658

255	26.83	21.00	20.00	0.2073	3.5299	2.3382	1.1917	66.24	0.1111	33.4471	0.1275	4.664	21.090	7.516	0.80	1.659
257	24.00	20.00	18.00	0.1791	2.9839	2.0640	0.9199	69.17	0.1120	33.4471	0.1403	5.063	20.692	7.126	0.80	1.573
259	26.00	21.00	19.50	0.1987	3.3614	2.2669	1.0945	67.44	0.1129	33.4470	0.1307	4.781	20.973	7.403	0.80	1.635
261	26.17	20.25	18.00	0.2004	3.3954	2.0640	1.3314	60.79	0.1137	33.4470	0.1403	5.080	20.674	7.312	0.80	1.614
263	24.00	18.00	17.00	0.1791	2.9839	1.9377	1.0462	64.94	0.1146	33.4470	0.1465	5.143	20.611	7.098	0.80	1.567
265	28.00	19.50	20.50	0.2201	3.7799	2.4116	1.3683	63.80	0.1155	33.4469	0.1241	4.448	21.307	7.691	0.80	1.698
267	26.50	19.50	17.00	0.2039	3.4621	1.9377	1.5244	55.97	0.1163	33.4469	0.1465	5.250	20.504	7.279	0.80	1.607
269	26.83	20.00	17.00	0.2073	3.5299	1.9377	1.5922	54.89	0.1172	33.4469	0.1465	5.286	20.468	7.294	0.80	1.610
271	25.00	19.50	17.50	0.1887	3.1678	2.0000	1.1678	63.14	0.1181	33.4468	0.1434	5.139	20.615	7.190	0.85	1.687
273	26.33	17.25	18.50	0.2021	3.4276	2.1298	1.2978	62.14	0.1190	33.4468	0.1371	4.764	20.990	7.437	0.85	1.745
275	24.17	20.25	15.00	0.1807	3.0145	1.7053	1.3092	56.57	0.1198	33.4467	0.1585	5.739	20.015	6.908	0.85	1.621
277	27.33	19.25	19.50	0.2127	3.6350	2.2669	1.3681	62.36	0.1207	33.4467	0.1465	5.232	20.522	7.354	0.85	1.725
279	28.33	20.25	20.50	0.2238	3.8532	2.4116	1.4416	62.59	0.1216	33.6700	0.1241	4.493	21.433	7.763	0.85	1.821
281	27.83	21.25	20.00	0.2182	3.7427	2.3382	1.4045	62.47	0.1224	33.4466	0.1275	4.680	21.074	7.593	0.80	1.093
283	27.83	21.75	21.00	0.2182	3.7427	2.4870	1.2557	66.45	0.1233	33.4466	0.1208	4.464	21.290	7.671	0.80	1.105
285	27.00	21.50	20.50	0.2092	3.5653	2.4116	1.1537	67.64	0.1242	33.4466	0.1241	4.570	21.183	7.563	0.80	1.089
287	29.17	20.50	20.00	0.2335	4.0452	2.3382	1.7070	57.80	0.1251	33.4465	0.1275	4.632	21.122	7.717	0.80	1.111
289	27.67	22.00	20.50	0.2164	3.7079	2.4116	1.2963	65.04	0.1259	33.4465	0.1241	4.602	21.152	7.608	0.80	1.096
291	27.33	21.75	20.50	0.2066	3.5299	2.4116	1.1183	68.32	0.1268	33.4465	0.1241	4.586	21.168	7.537	0.80	1.085
293	26.50	21.25	21.00	0.2320	3.9400	2.4870	1.4530	63.12	0.1277	33.4464	0.1208	4.434	21.320	7.780	0.80	1.120
295	28.33	20.50	19.50	0.2238	3.8532	2.2669	1.5863	58.83	0.1285	33.4464	0.1307	4.748	21.005	7.608	0.80	1.096
297	28.33	21.75	20.50	0.2050	3.5299	2.3382	1.1917	66.24	0.1294	33.4463	0.1275	4.712	21.042	7.480	0.80	1.077
299	27.50	21.50	20.50	0.1851	3.1678	2.3382	0.8296	73.81	0.1303	33.4463	0.1275	4.696	21.058	7.311	0.80	1.053

(17th August, 2013 = DOY 229 and 26th October, 2013 = DOY 299)

Key: DOY = Day number of the year, T = Greenhouse air temperature, Tm = Mean greenhouse air temperature, Td = Dew point temperature, Δ = Slope of saturation vapour pressure curve, e^a = Actual vapour pressure, e^o = Saturation vapour pressure, RH = Relative humidity, D = Constant, Rso = Daily clear day solar irradiance, ε′ = Net emissivity, Rln = Net longwave radiant energy, Rn = Net radiant energy, ETo = Reference evapotranspiration, P = Shading factor by canopy, CWR = Crop water requirements.